SOIL-LANDFORM RELATIONSHIPS ON BULLOCK CREEK FAN, NORTH CANTERBURY.

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Abstract of a thesis submitted in partial fulfilment of the requirements for the Degree of M.Appl.Sc.

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Steep slopes prone to mass wasting processes such as debris flows cause extensive damage on hill country farms and adjacent lowlands. Fan activity is episodic and can be deciphered using soil stratigraphic techniques.

Bullock creek fan is an active, debris flow dominated fan, covering 300 hectares. The fault shear zone on the eastern flank of Mount Thomas provides an abundant and easily eroded source of brecciated siltstones and highly fractured sandstones. The resultant fan sediments are mainly sandy matrix supported, gravelly to bouldery debris flow deposits and finer, massive or laminated sheet flood deposits.

Five geomorphic surfaces have been recognised. The soils that characterise the three late Holocene surfaces, displayed increasing development from Fluvial Recent Soils (Entisols-USA), to Stony Brown Soils (Inceptisols-USA). Orthic Brown Soils (Aquepts-USA) formed in mixed loess and gravelly alluvium occurred on a mid to early Holocene surface, and Fragic Pallic Soils (Fragiaquepts-USA) were formed in 2.5 metres of loess overlying a Late Pleistocene surface.

In areas of thinner, sheet flood deposits, on the younger geomorphic surfaces, multisequal soil profiles with evident buried horizons were more common than unisequal soil profiles. By comparison, the thicker, debris flow lobes displayed a gradient of multisequal to unisequal soil profiles, from the edge to the centre of the lobes. Much of the detailed history of recent fan activity could be interpreted from the stratigraphy and distribution of multisequal soil profiles. With increased soil development and surface age, multisequal soils evolved to take on the morphological characteristics of unisequal soils and the details of earlier fan activity could only be broadly interpreted.

The current period of fan activity has been occurring since the early 1900's, producing a surface, dominated by Fluvial Recent Soils, which covered 60% of the fan. In excess of ten deposition events were recognisable from the stratigraphy in the multisequal Fluvial Recent Soils. There has been significant aggradation on the mid and lower segments of the fan. Sedimentation since 1978 has been largely confined to the back-filling of a fan head trench and valley floor.

Soil development and the re-establishment of pastures on the aggrading fan surface had been enhanced by the texture and natural fertility of the sediments. Sheet flood deposits produced more easily cultivated soils because of their finer and more uniform soil textural properties and better moisture regime.

Further phases of fan aggradation, caused by erosion of stored sediments in the valley floor and fan head, are anticipated in coming decades.

Keywords:

Bullock Creek fan, soil stratigraphy, debris flow, hyperconcentrated flow, sheet flood, geomorphic surface, soil development, multisequal soil, unisequal soil, fan aggradation.

FRONTISPIECE.

Plate of the Bullock creek drainage basins, valley floor and fan.

be consistent.

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CHAPTER 1
INTRODUCTION

CHAPTER 1.0 INTRODUCTION.

1.1 Background to study.

Steep slopes are prone to mass wasting processes, such as debris flows. Debris flows often cause extensive damage to hill country farmland and adjacent lowlands. A large proportion of this farmland is situated on fans produced by the episodic activity of debris flows. Soil stratigraphic methods can be used to decipher the erosional and depositional history recorded in the stratigraphy of the fan.

1.2 Objectives.

The objectives of this study were to develop a model, of the soil landform and the soil stratigraphic relationships, for the Bullock Creek fan and to use these model relationships in the interpretation of the erosion and deposition periodicity within the Bullock Creek drainage basin. The impact of debris flow related activity on landuse was to be assessed also.

CHAPTER 2
TRANSPORT PROCESSES, MORPHOLOGY AND SEDIMENTOLOGY OF FANS

CHAPTER 2.0 TRANSPORT PROCESSES, MORPHOLOGY AND SEDIMENTOLOGY OF FANS.

2.1 The fan environment.

Fans are distinct terrestrial landforms found in diverse depositional environments. Their surfaces form a segment of a cone radiating downslope from the point where the stream leaves the source area.

Each source area consists of one or more drainage basins from which erosional products are transported to the fan apex via a single trunk stream (Bull, 1977).

Fans form where there is a decreased confinement of stream flow, resulting in a change in hydraulic geometry (Bull, 1964a; Harvey, 1989), and decreased flow competence. Wasson (1975), states a change in confinement of the channel may be accompanied by a decrease in gradient, facilitating fan construction by reducing the rate of sediment transport. Slope is also smoothed by the disposition of the fan apex radially, termed as the "intersection point" by Hooke (1967).

Debris flows have been observed flowing unconfined (Okuda, Suwa, Okunishi, Yokoyama and Nakano, 1980; Pierson, 1980a), suggesting a change in hydraulic geometry is not primarily responsible for deposition where debris flows are concerned. Debris flows are homogeneous, not able to selectively deposit their loads relative to flow competence but are instead dependent on initial momentum. A decrease in slope as suggested by Wasson (1975), may be more applicable to debris flow dominated fan formation.

Fans are undoubtedly common to a variety of landscapes (eg. intermontane basins, valleys and foothills of mountainous regions), irrespective of climatic conditions.

Many authors are of the opinion that fans are characteristic of contemporary arid and semi-arid climates. This general misconception has arisen because the largest, best preserved and the most studied fans lie in the foothills of mountains in the drier regions, notably the southwest United States (Blackwelder, 1928; Beaty, 1961; Bull, 1964b).

Harvey (1989) states that arid environments are conducive of the conditions favouring fan formation, such as high sediment supply and a sudden decrease in stream power at mountain front locations.

Episodically high rates of sediment production and delivery have propagated the idea that debris flows are produced in arid and semi arid environments.

Wasson (1977b), Kochel and Johnson (1984), Eggleston (1989) and others described fans dominated by debris flow deposition in non-arid environments. Evidence of debris flow and associated processes in humid-temperate climatic environments is often "masked" by the low frequency of debris flow causing rainfall events. An overall increase in rainfall however, results in considerable fluvial reworking of debris flow deposits and the rapid re-establishment of vegetation, both of which alter fan processes or hinder the recognition of past fan processes.

Vegetation between periods of active stream flow deposition gradually altered braided, active channels to a more sinuous, inactive channel pattern on an alluvial fan in Costa Rica (Kesel, 1985).

2.2 The fan system.

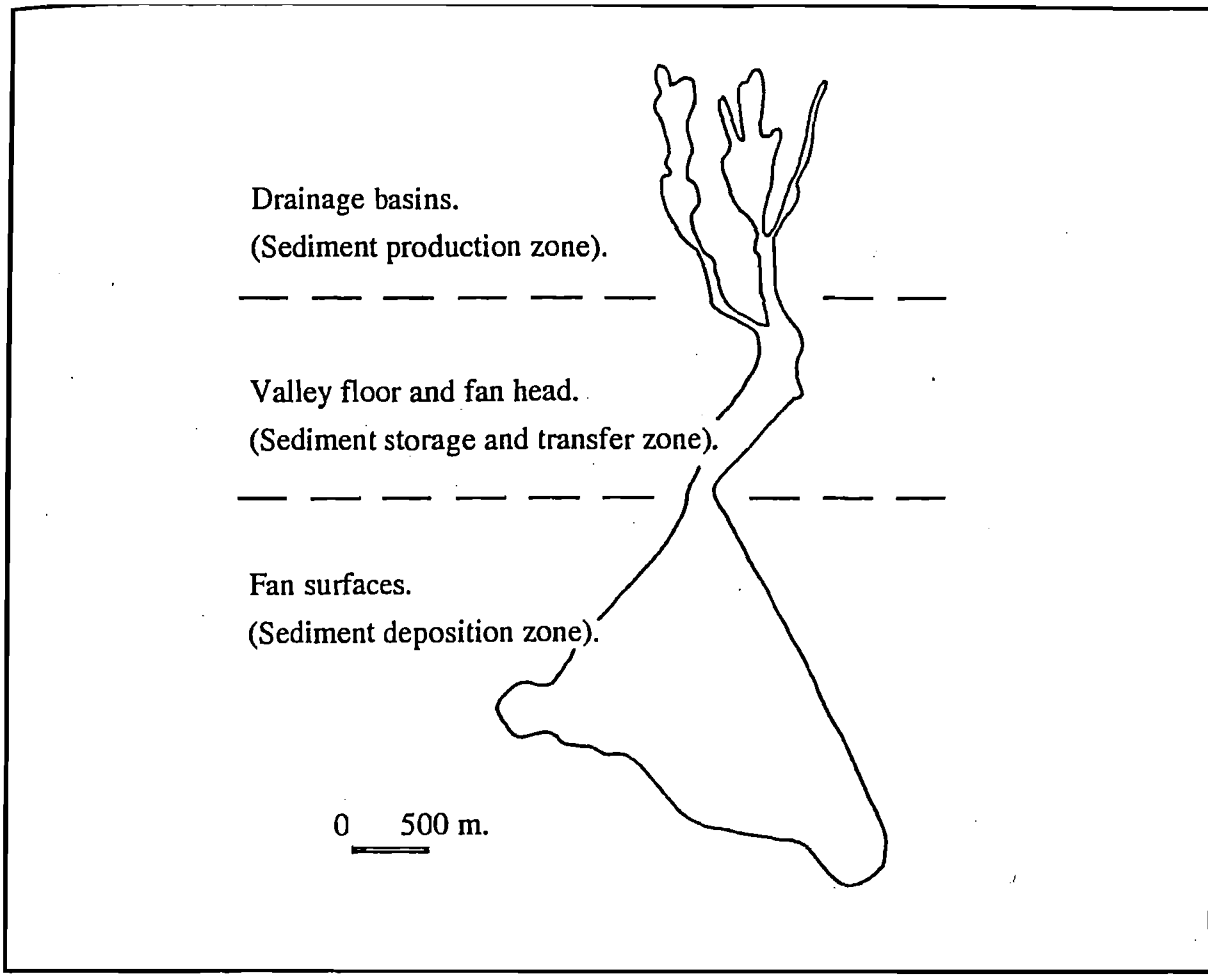
In this study the fluvial system model (Schumm, 1977), has been adopted to explain the fan fluvial system and its' components.

This involved:

1. The examination of the requirements and initiation of transport processes within the debris flow-fluvial flow continuum in the source zone.
2. The identification and description of sediment transport processes in the transfer zone.
3. The recognition and description of deposition processes and resulting depositional surfaces in the deposition zone.

A prerequisite to understanding fan formation is the recognition that sediment production, transport and deposition processes are all part of a complex response system. The fan is a depositional landform and can be considered as the depositional zone within the fluvial system. Knowledge of the quantity and type of sediment, the manner in which water is supplied from the source area, the external controls on that sediment and water supply within the fluvial system is required. The idealised fluvial system model (Schumm, 1977), provides for this (Figure 2.1).

Figure 2.1. An idealised fluvial system model for the fan system (adapted from Schumm, 1977).



The fluvial system model consists of three zones each dominated by different geomorphic and dynamic processes (Schumm, 1977).

The uppermost zone (Zone 1), consists of the drainage basins where the majority of water and sediment enter the system. To a lesser extent sediment is stored and sediment transport processes are initiated. The trunk stream channel and valley floor make up the transport and storage zone (Zone 2). This zone provides a buffer region between erosional and depositional zones within the system. Zone 3 is dominated by sediment deposition, forming the surfaces of the fan or piedmont.

The model assumes the zones to be interactive with preceding zones determining the events further down the system.

2.3 The threshold concept.

Erosion and deposition are seldom continuous, but instead may be separated by periods of relative stability. Schumm (1973), concluded that the presence of thresholds influenced geomorphic change within the fluvial system.

Thresholds are usually considered in terms of the external stress applied to the system and the strength of the materials to which the stress is applied. These determine the stress conditions under which geomorphic change results (Schumm, 1977). However this explanation does not accommodate for the situation where landforms under identical environmental conditions (external stresses), in the same region differ in geomorphic development. Schumm (1977) and Schumm, Mosely and Weaver (1987), concluded that both external (extrinsic) and internal (intrinsic) factors controlled geomorphic stability; excedence of extrinsic or intrinsic thresholds resulting in geomorphic instability.

Extrinsic thresholds are exceeded by external stresses or processes such as tectonic activity and climatic change which may act progressively or abruptly resulting in rapid erosion and deposition.

An intrinsic threshold is indicated by a change that occurs independent of any external variable change.

The geomorphic threshold is an intrinsic threshold, inherently developed within the geomorphic system by changes in the system itself through time (Schumm, 1977). Fan head trenching provides a good example of the influences of extrinsic and intrinsic factors on the geomorphic system.

Wasson (1977a) makes the distinction between fan incision and fan dissection. The former is a result of intrinsic factors and is normally a temporary migration of deposition down fan with associated fan head incision. The latter is a result of extrinsic factors acting to produce fundamental regime changes. Further examples of intrinsic and extrinsic factors are given in Heward (1978) and Eggleston (1989).

2.4 Transport processes and deposition.

2.4.1 Introduction.

Sediment transport through the fan system depends on the transport process and transporting power. Variation within or between processes may place parts of the system out of phase with one another, sediment accumulating in some reaches and being eroded in others (Schumm, Mosley and Weaver, 1987).

Fan transport and depositional processes comprise the two groups of stream flow and debris flow (Bull, 1977). More recently an intermediate flow type (termed hyperconcentrated flow) has been separately recognised (Costa, 1988; Davies, 1988; Smith and Lowe, 1991).

Hyperconcentrated flows are intermediate in nature between dilute, turbulent, normal stream flow and viscous, dominantly laminar debris flow (Smith and Lowe, 1991). They are regarded as a separate group in this study to highlight their importance.

In reality stream flow and debris flow processes represent the extremes of a flow continuum based on flow character and sediment-water concentration (Costa, 1988). Separation and classification of the flow groups is based on inherent, unique and diagnostic flow properties, (Table 2.1).

Table 2.1. General rheological classification of water and sediment flows in channels (after Costa, 1988).[1]

Flow	Water flood (stream flow)	Hyperconcentrated flow	Debris flow
Sediment concentration	1 - 40% by wt. 0.4 - 20% by vol.	40 - 70% by wt. 20 - 47% by vol.	70 - 90% by wt. 47 - 77% by vol.
Bulk density (g/cm^3)	1.01 - 1.33	1.33 - 1.80	1.80 - 2.30
Shear strength ($dyne/cm^2$)	0 - 100	100 - 400	> 400
Fluid type	newtonian	non-newtonian (?)	viscoplastic (?)
Major sediment-support mechanism	electrostatic forces, turbulence	buoyancy, dispersive stress, turbulence	cohesion, buoyancy, dispersive stress, structural support
Viscosity (poise)	0.01 - 20	20 - ≥ 200	>> 200
Fall velocity (% of clear water)	100 - 33	33 - 0	0
Sediment concentration profile	non-uniform	non-uniform to uniform	uniform
Predominant flow type	turbulent	turbulent to laminar	laminar

2.4.2 Stream flow.

During stream flow sediment and water are two distinct and separate phases. Flow is fully turbulent with sediment supported and transported in suspension (electrostatic charges and turbulence are the primary support mechanisms), and by rolling and saltating along the channel floor as energy is transferred from water to sediment (Costa, 1988). Pierson and Costa (1987) defined stream flow as flowing water with a sufficiently small sediment concentration that its flow behaviour remained unaffected by the presence of sediment in transport (i.e. it is a Newtonian fluid). Stream flow is represented by the tractive-dominated, grain by grain sediment deposition mechanisms (Smith, 1986). The type and size of the sediment transported is largely dependent on the energy of the flow.

[1] Assumes silt and clay content <10%

2.4.3 Debris flow.

2.4.3.1 Requirements for debris flows.

A clear relationship between process and form has been identified by Denny (1967) and Kostaschuk, MacDonald and Putnam, (1986). Process-form relationships differ for different fan types. This has been attributed to the character of the drainage basin(s), its' regolith, vegetation and exposure to precipitation.

Innes (1983) states that a fundamental difference must be made between the conditions required for debris flow activity and the conditions initiating activity.

The prerequisite requirements for debris flow activity are specific and absence of any of the conditions usually results in domination of fluvial sediment transport.

Drainage basin character.

Progressively smaller and steeper basins have a greater potential for debris flow activity. This is because firstly, rainstorms drop proportionally larger volumes of water per unit time on smaller basins. Secondly smaller basins are usually at high altitudes and prone to snow accumulation. Finally slopes are steeper and more rugged (Costa, 1984).

A slope of 30 degrees is given as the minimum for hillslope activity (Brunsden, 1979; Costa, 1984), 32 to 42 degrees in Scotland (Innes, 1983) and 25.5 degrees by Rapp and Nyberg (1981). However, drainage basin floor slopes of 15 to 20 degrees were sufficient for debris flow initiation where confined side slopes were between 75 and 80m degrees (Innes, 1983).

Regolith.

Debris flows require an abundance of poorly sorted, unconsolidated, coarse and fine sediments (Costa, 1984; Beaty, 1990). The size of the weathered products is important with joint spacing being a determining factor (Beaty, 1990).

In the White mountains, United States, the sediments include massive granite boulders, closely jointed metamorphic and sedimentary bedrock producing smaller sediments (Beaty, 1990).

Finer shale and slate sediments combined with boulders of basalt and limestone dominate the Hunshui gully, china (Li and Luo, 1981). Here large tectonic movements (magnitude 8 to 9), produced large collapses and landslides covering 14.3 percent of the drainage basin area.

Wells and Harvey (1987), found major sources of sediment to include:

1. Fine grained sediment and subangular to angular clasts from soliflucted till exposed on hillslopes and in the fossil gully walls.
2. Angular blocks of siltstone and sandstone bedrock.
3. Subangular to subround boulders, gravels and finer sediments.

Beaty (1990) noted the importance of the transfer of sediments from drainage basin side slopes to the floor. Processes acting on the canyon walls included direct gravity fall, wet mass movements and erosion by running water.

A number of studies have highlighted the need for sediment build up in the drainage basin and valley floor, (Innes, 1983; Suwa and Okuda, 1983; Beaty, 1990). A large volume of available sediment is required for debris flows to occur, consequently flows are often associated with channels containing deep beds of widely graded sediment (Davies, 1988).

Debris flows have specific water to sediment ratios (weight to weight ratio of 1:4). Crucial to this is the availability of fine sediments (silt and clay), which provide the supporting matrix for the large clasts (Harvey, 1989).

Innes (1983) and Johnson and Rodine (1984) stated that increased regolith clay content increases soil saturation, facilitating the debris flow process. Measurements of clay content have been low (3 to 20 percent), (Pierson, 1980a; Innes, 1983), suggesting slight increases may dramatically accelerate soil saturation and subsequent debris flow occurrence.

Precipitation.

Precipitation is the most documented factor concerning debris flow occurrence. Common moisture sources are rainfall (Caine, 1980; Innes, 1984; Wells and Harvey, 1987; Kochel, 1987), snowmelt, (Sharp and Nobles, 1953) and rapid drainage of volcanic craters (Smith, 1989; Pierson and Scott, 1985). Smith (1991) noted that many volcanic debris flows were a result of rapid snowmelt caused by volcanic activity.

Caine (1980) stresses rainfall as a factor indirectly effecting pore water conditions in the soil. This point was also emphasised by Davies (1988).

Not all rainstorms give rise to debris flows, even in regions where they are prone to occur frequently. There is a requirement that the duration of rainfall sufficiently saturates the available sediment and pore water pressure is increased to a point where failure occurs. Debris flows are commonly observed following intense rainfall bursts during these long duration rainstorms (Okuda *et al.* 1980; Pierson, 1980b; Kesel, 1985; Wells and Harvey, 1987; Kochel, 1987).

Threshold conditions for debris flow differ depending on the lithological properties of the regolith. For a given regolith an upper intensity limit is defined by the point at which failure occurs prior to the debris being fully saturated. The lower limit is at a position where failure will not occur even at saturation (Takahashi, Ashida and Sawai, 1981).

Vegetation.

Sparse vegetation is given as a prerequisite condition for most debris flow activity (Costa, 1984), further fostering the idea that debris flows only occur in arid regions. The scarcity of vegetation however, is more likely to be a reflection of very unstable and steep sloped drainage basin character which impedes vegetation establishment. Studies in north

Westland, New Zealand (O'Loughlin, 1974), found that downslope movement of soil and rock materials *en masse* occurred on forested hill country. Debris flows are common in humid-temperate environments where vegetation is prolific (Kochel, 1987; Ono, 1989).

Vegetation, its absence or presence strongly influences soil moisture distribution and pore water pressure (O'Loughlin, 1974). Any modification of vegetation would therefore have implications for drainage basin hydrology and slope stability.

Implications include:

1. Increase in water interception at the soil surface, coupled with a decrease in canopy detention and evapotransporation.
2. The soil/ sediment store reaches saturation more rapidly for a given rainfall intensity/duration event.
3. Saturation of the soil/sediment store and the loss of root shear strength lowers failure thresholds, therefore increasing the possibility of failure and subsequent debris flow activity.

More frequent activity has been attributed to the recent removal of vegetation from drainage basins (Beaty; 1963, Li and Luo, 1981; Pierson, 1980a; Beaty, 1990).

The continued destruction of forest vegetation has over the past 300 to 400 years resulted in a proportional increase in mudflow activity in the Hunshi and Quinshui gullies, southwest China (Li and Luo, 1981).

Brazier, Whittington and Ballantyne (1988) attributed the destruction of natural vegetation cover to the reactivation of fluvial activity and possibly mass movement in Scotland.

2.4.3.2 Debris flow processes.

The initial failures leading to debris flows include slides, slumps, toppling or the instability of channel deposits (Costa, 1984). The exact transformation from planer or rotational mass wasting to debris flow is not certain, although there seems to be a critical point prior to debris flow where remoulding of sediment occurs with the addition of water (Hampton, 1972).

In debris flows solid particles and water move in phase as a single viscoplastic body (Johnson, 1970), with sediment entrainment irreversible, that is the flow cannot deposit any but the coarsest particles flow velocity decreases (Costa, 1984, 1988).

Debris flows vary widely in character, from very high density (~2.5 Tm^{-3}), extremely intermittent flows (Davies, 1988), to more dilute "runout" flows as described by Pierson (1980a) and Wells and Harvey (1987).

They may follow pre-existing channels or move across unobstructed, laterally unconfined fan surfaces, building their own channels as levees (Sharp and Nobles, 1953; Pierson, 1980a; Costa, 1984).

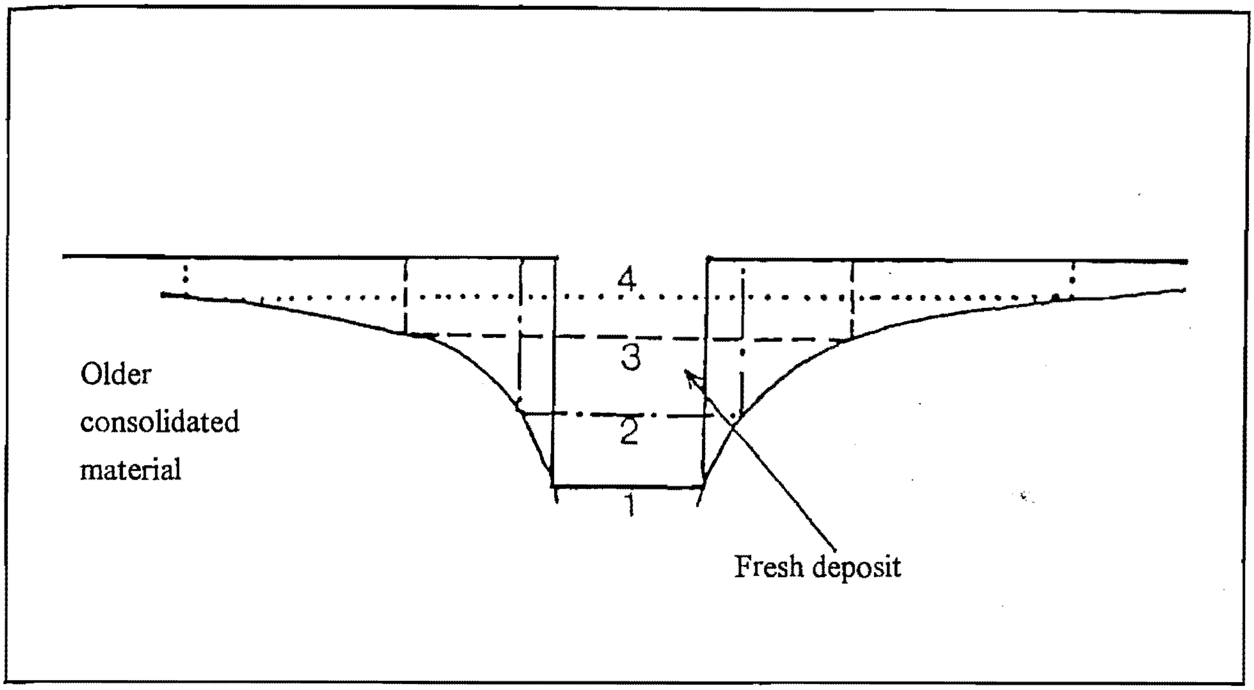
The ability of debris flows to travel over low slopes has been attributed to the presence of clay in the flow. As little as 1 to 2 percent clay content reduces permeability, increases pore water pressure and greatly increases mobility (Costa, 1984). Dilution of debris flows also allows flow over low angle surfaces (Pierson and Scott, 1985; Wells and Harvey, 1987).

Pulsing flows separated by continuous and less viscous flows have been described by Pierson (1980a) and Li and Luo (1981). It was previously thought that pulsing flow, characteristic of debris flows was generated by the entry of a landslide into the stream channel. A temporary dam forms with subsequent mobilisation of sediment caused by rising water levels upstream. This results in a surge wave travelling downstream (Davies, 1985,1986). Davies (1988) stipulated that the pulsing behaviour of large debris flows was caused by an intrinsic instability. A roll-wave instability of flowing material was first used to explain the coalescence of small random surges into large regular surges downstream. Although proven theoretically (Davies, 1988) this idea was not substantiated in the field (Davies, Phillips and Zhang, 1991). Instead Davies *et al.* (1991) postulated that the continued input of sediment into the stationary sediment in the upper reach during surges would effectively increase local slope and sediment depth at the upstream reach. Increased local shear yield stress would result with excedence of this stress threshold immediately setting the slurry in motion.

Debris flows are highly erosive, capable of scouring large U-shaped channels (Pierson, 1980b, Li and Luo, 1981; Davies *et al.* 1991). This canyon-like morphology is a characteristic of many debris flow gullies.

Davies *et al.* (1991) attributed the rapid incision and minimal lateral erosion to the upstream regression of knickpoints. Knickpoints originated where there was deep scouring of the channel bed in channel bends. Subsequent flows excavated the channel bed immediately downstream, undermining the scour edge and resulting in the formation of a narrowing channel. Following a debris flow event stream flow may laterally erode these narrow channels as illustrated in Figure 2.2.

Figure 2.2. Widening and infilling of scour trench (after Davies *et al.* 1991).



Similar observations were made at Mount Fitzwilliam, New Zealand by Pierson (1980b), where channels were up to 10 metres deep.

Debris flows are capable of transporting large clasts for long distances on gentle slopes (Costa, 1984). Beaty (1963) noted boulders greater than 10 metres in diameter being transported several kilometres down fan.

Boulders appear to "float" or weakly tumble along in the flow surface (Costa, 1984). A number of models have been proposed to explain this phenomena (Hampton, 1979; Costa, 1984; Davies, 1988; Beaty, 1990).

They have included:

1. The cohesive strength of fine sediments in the flow (Hampton, 1976; Rodine and Johnson, 1976).
2. Buoyancy due to the excess pore water pressure within the flow body (Hampton, 1979; Pierson, 1981).
3. Dispersive pressure caused by intergranular contact stresses resulting from grain shearing (Bagnold, 1956; Takahashi, 1980).

Davies (1988) proposed that the ability of a debris flow to transport large clasts depended on the occurrence of macroviscous grain shearing conditions associated with homogenous, viscous, coarse grained debris flows.

2.4.3.3 Hyperconcentrated flow processes.

Hyperconcentrated flows have long been recognised as important in subaqueous sedimentation (Lowe, 1982; Middleton and Southard, 1984). Recently terrestrial volcaniclastic flows (Pierson and Scott, 1985; Smith, 1986) and non-volcanic flood flows (Costa 1988; Davies, 1988) have been identified as possessing similar characteristics as the subaqueous flows.

Pierson and Scott,(1985) noted that at extreme sediment concentrations, coarse lithic sand and low density gravels were suspended in the flow, suppressing secondary turbulence and giving the flow an oily, glassy, smooth appearance. Similar observations were made of slurry-like flows during debris flow activity by Pierson (1980a).

Pierson and Costa (1986) defined hyperconcentrated flow as a flowing mixture of water and sediment that possessed a measurable yield strength but still appeared to flow as a liquid. Smith (1986) described them as high discharge flows in which turbulence is not the lone sediment support agent and deposition does not occur *en masse*.

Beverage and Culbertson (1964) introduced the term hyperconcentrated flow for flows in which a combination of buoyancy, grain interactions and dampened turbulence contributed to grain support (Smith and Lowe, 1991).

Recognition of hyperconcentrated flow using depositional criteria (Smith, 1986) differs from the rheological constraints of Pierson and Costa (1988), creating an overlap between stream flow (producing sheetflow and shallow braided stream facies) and hyperconcentrated flow. Linking of the process mechanisms and resulting deposits is required. Until this is achieved Smith and Lowe (1991) suggest defining hyperconcentrated flows as non-Newtonian fluid-solid mixtures possessing little or no strength and generating deposits intermediate in nature to those resulting from debris flow and stream flow.

There seems to be no continuous variation of behaviour between flow extremes (Davies, 1988). Hyperconcentrated flow occurs as near continuous slurry waves separating viscous surges (Pierson 1980a; Davies, 1988), or following the transition from downstream dilution of debris flows (Pierson and Scott, 1985; Smith, 1991).

Studies on volcaniclastic flows (Fisher, 1983; Pierson and Scott, 1985) highlighted the transformation from one flow type to the other during movement.

Fisher (1983) defined flow transformation as changes in flow behaviour between laminar and turbulent states. Humid environments are more conducive to downstream hydrological variations (Major and Newhall, 1989), therefore flow transformations may be more apparent in such regions.

Dilution occurs when debris flows over-run slower velocity stream flows. Mixing of the turbulent stream water with the moving debris flow front results in dilution to a hyperconcentrated flow state. Pierson and Scott (1985) documented such a transformation that occurred over a 24 kilometre distance at Mount St. Helens, United States. Here the downstream dilution transformed the debris flow through the flow continuum to stream flow. Pierson and Scott (1988) and Scott (1988) stated that all hyperconcentrated flows were generated in this manner and showed a good correlation with upslope debris flow events.

Smith (1991) also stipulated that some flows may bulk up or dilute to become hyperconcentrated flows. In hyperconcentrated flows as in stream flows, solids and water move as separate components. Vertical turbulence fluctuations keep sediment in suspension through viscous drag on particles, smoothing out large scale fluctuations and decreasing turbulence. Buoyancy and dispersive stress play a greater role as sediment concentration increases (Costa, 1984, 1988).

2.5 Fan morphology.

2.5.1 Gross morphology.

Basic fan form is not a product of a particular flow type, but arises from a change to unconfined flow (Bull, 1977) and excess sediment load (Hooke, 1967; Kostaschuk *et al.* 1986). However according to Denny (1967) process determines form (that is the two are indivisible), thus gross morphology and surface form (micromorphology), depend on the mode of deposition.

Stream flows and hyperconcentrated flows vary their sediment loads readily by deposition or erosion (depending on flow competence) and will continue to flow given that slope exists.

Hyperconcentrated flows behave in a similar way to stream flows but are differentiated by a high proportion of suspended sediment and dampened turbulence (Costa, 1988).

All processes may occur on a fan either during a single storm event (Costa, 1984) or over several events (Harvey, 1989). Observations of facies sequences by Wells and Harvey (1987) revealed a transition during a single storm from an early phase of stream flow to debris flow and hyperconcentrated flow, returning back to stream flow at the end of the storm.

Usually one process dominates on a fan, resulting in fans of different gross morphologies (Kostaschuk *et al.* 1986).

The typical fan is radially concave and laterally convex (Bull, 1977). Fan size is controlled mainly by drainage basin characteristics such as size, slope, interception of rainfall and stability of exposed rock (Bull, 1964b). The relationship between drainage basin size and slope has been expressed by Bull (1977) in the following equation:

$$A_f = cA_d^n \qquad \begin{array}{l} A_f = \text{fan area} \\ A_d = \text{drainage basin area} \\ c = \text{constant} \end{array}$$

Fan shape is influenced by fluid momentum and channel confinement at the fan head. For confined flow fluid momentum is of greater importance with debris flows which have greater momentum than fluvial flows for a given water discharge. This is the case with arid region fans (Bull, 1977) which display an elongate constructional form. Using experimental model fans Rachocki (1988) noted that confinement of the channel at the fan head produced fans subtending greater than 180 degrees, whereas fans unconfined at the fan head subtended 90 degrees.

Fan elongation resulted from valley confinement on humid fans in the Appalachins (Kochel, 1990).

Generally fan slope decreases with increasing fan area and drainage basin size (Bull, 1962a; 1977). On alluvial fans channel slope approximates fan slope and is a function of discharge and sediment size. Sediment transport is selective, consequently low angle fans are formed.

Conversely debris flow fans are steep sloped, a result of debris flows being a function of sediment availability, sorting, clay content and initial momentum.

Table 2.2 shows the effect of particular depositional modes on fan slope (Bull, 1977; Hooke, 1968).

Table 2.2. The relationship between depositional mode and fan slope (after Bull, 1977).

Slope	Steepest slopes				Most gentle slopes
Dominant mode of depostion	sieve	sieve	debris flow	water-laid	fine grained water-laid
Other modes of deposition	none	debris flow	water-laid	debris flow	none

2.5.2 Fan surface morphology.

Geomorphic and sedimentologic criteria have been used (Costa and Jarrett, 1981; Costa, 1984, 1988) to ascertain process rather than using sediment concentration boundaries or thresholds that, at present are poorly defined.

According to Costa and Jarrett (1981) the criteria used to relate process to form depends on the following:

1. The presence of coarse, poorly sorted levees and terminal lobes on fan surfaces and bordering channels, indicating debris flows.
2. Sedimentology of deposits.
3. The extent of vegetation damage.
4. The extent of ground litter.

Interpretation is often complicated by reworking of deposits following deposition (Beaty, 1963; Hooke, 1967; Wasson, 1978; Costa, 1984).

Fluvial surface forms relate to include stream channels, sheetflow, bar and sieve deposits (Bull, 1977).

Kostaschuk *et al.* (1986) described a down fan transition from narrow, straight, incised braided channels at the fan apex through to the intersection point with the pattern becoming a series of anastomosing distributary channels.

Barforms are dominantly longitudinal or linguoid and often vary in distribution down fan (Boothroyd and Ashley, 1975). Changes in bar morphology observed by Kostaschuk *et al.* (1986) and Boothroyd and Ashley, (1975) found longitudinal bars dominated the upper fan and were often covered with transverse ribs. They were separated by incised channels. In the mid fan region lateral bars co-exisited with braid bars; interpreted as a complex multi-sinuous channel pattern by Ori (1982). The fan toe exhibited various bar forms, depending on channel pattern. Longitudinal and linguiod bars existed where the braiding channel pattern dominated. However the fan toe described by Bull (1977) and Kostaschuk *et al.* (1986) gave mainly point and longitudinal bars (to a lesser degree) within the shallow channels.

It has proven difficult to distinguish between hyperconcentrated flow and stream flow using geomorphic criteria (Costa, 1988). In most cases hyperconcentrated flows have produced morphology similar to the sheetflow deposits of stream flow. Sediment analysis is required to ascertain the origin of the deposit, and even this may be ambiguous.

Wells and Harvey (1987) described transitional flow deposits consisting of stacked lobes, broad superimposed mounds and small collapse depressions. These were thought to have originated from flows similar to the fluid slurries observed at Mount Thomas by Pierson (1980a).

Debris flows exhibit unique geomorphic characteristics. Numerous investigators have noted the following as indicating debris flow:

1. Marginal levees of poorly sorted clasts bordering channels.
2. Steep-fronted terminal lobes of coarse, poorly sorted sediments present on the fan surface and in channels.
3. Extensive vegetation damage in the direct flow path, but minimal damage except burial on gentle slopes and flow margins.
4. Deeply incised U-shaped channels with low width to depth ratios.
5. Presence of large boulders on the fan surface.

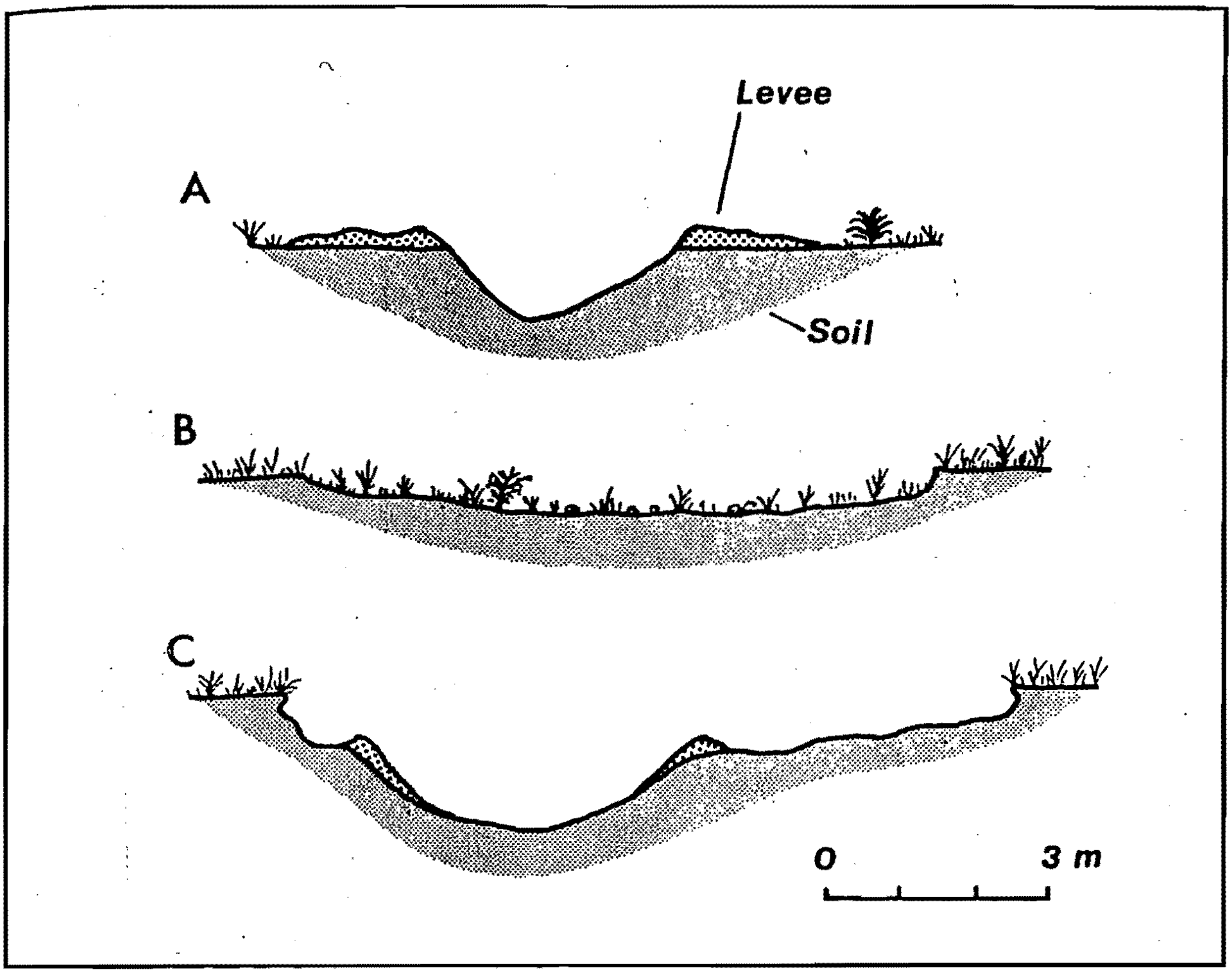
Beaty (1963) described flow deposits as long, relatively narrow strips extending radially from the apex to the fan margins. Debris flows overtopped channels producing small lobes and flatter sheetflows that extended "feather-like" from the breach point.

Debris flows may coalesce down the fan, spreading into slow moving fluid bodies with steep margins, flat tops and large imbedded boulders (Pierson, 1980a). They often fill surface irregularities, subduing relief (Wasson, 1977b).

Debris flows are often preceded or superceded by more fluid flows (Beaty, 1963; Hooke, 1967; Costa, 1984). Wells and Harvey, (1987) observed a range of geomorphic forms relating to variations within the flow regime. Surface forms varied in height, flank steepness, width and the presence of any micro-relief.

Often levee deposits and other surface forms associated with debris flows are reworked or destroyed either by subsequent debris flows or stream flow. Pierson (1980a) illustrated the long term changes of an incised debris flow channel and levees (Figure 2.3).

Figure 2.3. The cross sections of three debris flow gullies at Mount Fitzwilliam which depict a sequence from initial gully cutting (A), to infilling and revegetation (B), to reinitiation of debris flow activity and gully downcutting (after Pierson, 1980a).



Pierson (1980b) and Davies (1986) in suggesting that several flow types may exist within a single flow event recognised that channel morphology would also change. Following a debris flow event stream flow may re-establish in the narrow incised debris flow channels. This was illustrated previously in Figure 2.2. where meandering and braid channels forms cause lateral erosion of the channel sidewalls with sediments being redistributed as bedload. The net result is aggradation of the channel bed.

2.6 Fan sedimentology.

Sedimentary sorting and structure have been used to differentiate subaerial deposits (Costa, 1988; Wasson, 1977b).

Table 2.3 summarises the sedimentological characteristics of different deposits.

Table 2.3. Geomorphic and sedimentologic characteristics of water and sediment flows in channels (after Costa, 1988).

Flow	Landforms and deposits	Sedimentary structures	Sedimentary Characteristics
Water flood (stream flow)	Bars, fans, sheets, splays; channels have large width to depth ratio.	Horizontal or inclined stratification to massive; weak to strong imbrication; cut and fill structures; ungraded to graded.	Well sorted, clast supported; normally distributed; rounded clasts; wide range of particle sizes.
Hyperconcentrated flow	Similar to water flood	Weak horizontal stratification to massive; weak to strong imbrication; thin gravel lenses; normal and reverse grading.	Poorly sorted; clast supported open-work texture; predominantly coarse sand.
Debris flow	Marginal levees, terminal lobes, trapozidal to U-shaped channel.	No stratification; weak to no imbrication; inverse grading at base; normal grading near top.	Very poorly to extremely poorly sorted; matrix supported; negatively skewed; extreme range of particle sizes; may contain megaclasts.

Sediments can vary vertically and radially from the fan apex (Bull, 1977).

Bull (1963) separated deposits into three groups: debris flow, intermediate and water-laid. These were classified according to sorting, sedimentary structure and clast size and shape.

Wasson (1977b) modified this classification, placing the intermediate deposits into the water-laid group. This offered a simple means by which deposits could be recognised in the field. Classification was based on whether deposits possessed a rudimentary fluvial sedimentary structure or not.

2.6.1 Water-laid deposits.

Water-laid deposits include sheetflow, channel and sieve deposits (Bull, 1977; Harvey, 1989). Sheetflow deposits comprise thin sheets of gravels, sands or silt. Transport and deposition is by an integrated system of braided channels with surges of sediment-laiden water spreading out from the stream end (Bull, 1977). Deposits are very well sorted, cross bedded, laminated or massive lenses of gravels, sands and silt, associated with low bars and rapidly migrating shallow channel network (Bull, 1972).

Stream channel deposits result from the backfilling of channels entrenched into the fan (Hooke, 1967; Bull, 1977; Wasson, 1977b; Harvey, 1989). They are recognised by their channelled bases, internal bedding and lensed sedimentary structures, often by clast imbrication and better within sorting than sheetflow deposits (Harvey, 1989). Beds range in thickness 1cm and 200 cm, but are commonly between 5 cm and 100 cm thick.

Sieve deposits occur where source sediments contain little or no fine sediments. They are coarse, permeable, massive lobate deposits, displaying excellent sorting and poorly defined bedding contacts (Bull, 1977).

2.6.2 Debris flow sediments.

Debris flow sediments are massive, poorly sorted, matrix supported gravels (Harvey, 1989), which are placed in the facies Gms (muddy, sandy gravels) by Miall (1977). Inverse grading has been noted by Fisher (1971) and Naylor (1980).

Kochel and Johnson (1984) list the following as evidence supporting the occurrence of debris flow deposits:

1. Very poor sorting and coarse texture.
2. Indistinct stratification.
3. Sharp basal contacts.
4. Absence of current structures.
5. Super elevation of debris lines.
6. Inversely graded bedding.
7. Presence of rip-up clasts of soil.

Other textural indicators characteristic of debris flow deposits include positive skewness and bimodal size distributions (Sharp and Nobles, 1953; McArthur, 1987).

Deposits may grade into massive, clast supported muddy gravels (Miall, 1977). Wells and Harvey (1987) suggested that hyperconcentrated flows were responsible, however the washing of fines from the deposit matrix may also be responsible (Wasson, 1977b; Costa, 1988).

The smoothing affect of debris flow deposits has been documented by Johnson (1970) and Wasson (1977b), also explaining observed variations in bed thickness.

2.6.3 Hyperconcentrated flow deposits.

There is limited literature concerning these flows and deposits. Deposits intermediate between stream flow and debris flow deposits were recognised by Bull (1964) in the White Mountains and Wasson (1977b) in the lower Derwent Valley, Tasmania.

The process responsible was described as a slurry unlike debris flows and typic stream flow processes. Deposits are characteristically clast supported, poorly sorted and had mixed clast orientation. Facies originating from similar flows were described by Wells and Harvey (1987) as being locally stratified, clast supported with a collapsed fabric.

Sheet flood deposits described by Bull (1964) were recognised in the Cass Basin, Canterbury by McArthur (1987). They contained less silt and clay and were better sorted than the debris flow deposits described. McArthur (1987) postulated that they were produced towards the closing stages of fan building and contained interbedded channel deposits.

At Mount St. Helens, Washington State, hyperconcentrated flow deposits had coarse sandy textures with distinctly less fines than debris flow deposits. They were massive or had poorly developed horizontal stratification with thin gravel lenses, a clast supported, non-cohesive open-work structure and reversely graded sub-units (Scott, 1985; Costa, 1988).

Volcaniclastic flow sedimentology has been documented by a number of authors (Pierson and Scott, 1985; Smith, 1986, 1991). Smith (1986) identified two types of volcaniclastic hyperconcentrated flow deposits:

1. Fine (sand size), massive or weakly stratified deposits, normally or reversely graded without large sized stones or boulders common.
2. Coarser gravel deposits characterized by normal grading, no imbrication and an absence of intercalated sand lenses or beds typical of stream flow gravel.

Pierson and Scott (1985) and Scott (1988) described different deposits consisting of sands and gravels, massive or crudely stratified and clast supported. Normal grading dominated but inversely graded subunits did exist. Non-cohesive mass flows deposited the sediment in pulses by mass emplacement.

A range of characteristics should be expected in deposits, a factor which is dependent on the sediment to water conditions prevailing at the time of deposition.

2.6.4 Bedding.

Bedding of deposits has been one of the best methods of identifying the fan environment of deposition (Bull, 1972).

The character of deposits and deposition sequences reflect the particular set of hydraulic conditions present at the time of deposition, parameters such as bed thickness, clast size, distribution and orientation and bedding contacts (Bull, 1977).

Most fans comprise sheets of near uniform thickness. Debris flow fans studied in Virginia and North Carolina, United States, showed very little change in sediment character down fan, although beds were thicker near fan apices. No significant down fan textural variations were noted by Kochel and Johnson (1984). Bed thickness did not decrease down fan, however lateral variations in thickness were common due to the lobate nature of the debris flow deposits.

Fluvially dominated fans conversely varied in grainsize, as with the alluvial fans studied by McCraw (1968) in Otago, New Zealand, which displayed a decrease in sediment size down fan. Thickness varied from the proximal to distal facies, increasing to a maximum in the mid fan region, often exhibiting well defined stratification, dominated by thick horizontal beds (Kochel, 1990).

2.6.5 Packing.

Eggleston (1989) assessed the packing characteristics of sediments. Packing classes were established based on the characteristics of a deposit resulting from a specific flow type.

Table 2.4 outlines the major features associated with the established packing classes.

Table 2.4. Characteristics of packing classes (adopted from Eggleston, 1989).

Packing class	Associated flow	Class features
P1	Stream flow	Open packed, clast supported, loose, no matrix
P2	Stream flow-hyperconcentrated flow	Open packed, clast supported, loose, increasing proportion of matrix
P3	Hyperconcentrated flow-dilute debris flow	Close packed, matrix supported, high proportion of matrix to clasts, loose to compact
P4	Debris flow	Close packed, matrix supported, very compact, abundant matrix, extremely poorly sorted

For sediments with a high skeletal content a description of sedimentary packing assisted with the identification of flow types and the recognition of different soil development pathways.

CHAPTER 3
DETERMINING THE SOIL PATTERN

CHAPTER 3.0 DETERMINING THE SOIL PATTERN.

3.1 Debris mantle and the soil pattern.

Soil-landform analysis begins with an examination of the relationship between the soil pattern and established regolith patterns.

Eggleston (1989) distinguishes between the debris mantle and debris mantle regolith.

The debris mantle equates to the chemically unweathered, but includes physically weathered grade I sediments described in Table 3.1.

Table 3.1. Engineering geology classification of weathering grades for hard rocks (adopted from Fookes, Dearman and Franklin, 1971).

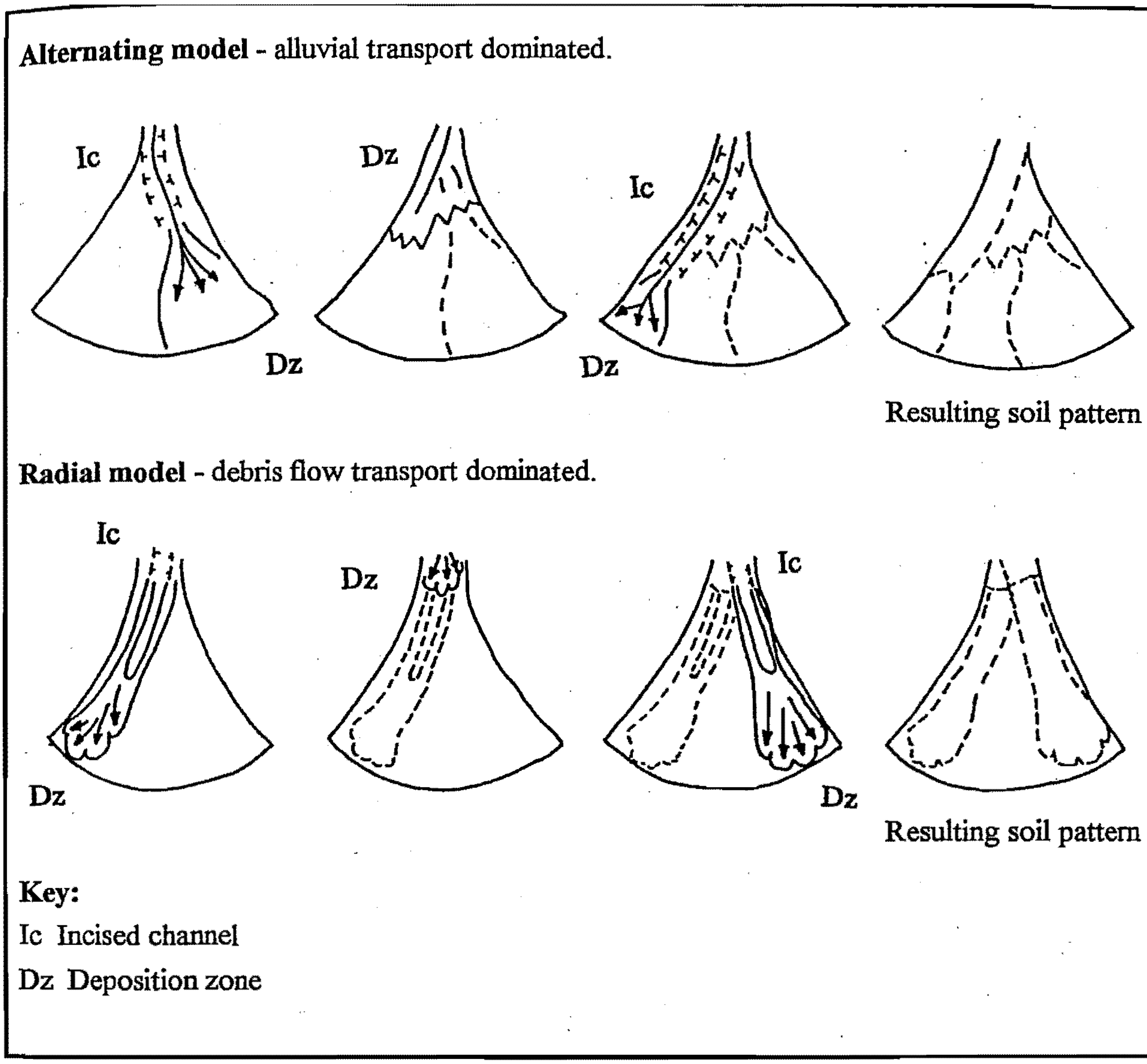
Degree of weathering	Grade	Description
Unweathered Fresh	I	Rocks show no discolouration or loss of strength or any other defects due to weathering. May have staining of defect surfaces (faintly weathered), but with no penetration of the rock fabric.
Slightly weathered	II	Rock may be slightly discoloured; defects or discontinuities may be open and have discoloured stained surfaces. Only slightly weaker than fresh rock.
Moderately weathered	III	Rock is discoloured throughout. Defects may be open and stained (usually iron and manganese oxides). Staining and decomposition partly penetrates the rock fabric, leaving a core of fresh rock. Noticeably weaker than fresh rock.
Highly weathered	IV	Rock is discoloured, defects may be open and stained or clay coated, some of the adjacent rock fabric is weathered to soil; weathering penetrated deeply inwards. Rock fabric persists and fresh core stones are usually present. Rock is severely weakened.
Completely weathered	V	Rock is discoloured, stained, and is completely decomposed to a soil, although the original rock fabric is mainly preserved. The properties of the soil depend in part on the nature of the parent rock.
Residual soil	VI	Rock is completely discoloured and decomposed to a soil with the original rock fabric completely destroyed. There may be a significant increase in volume.

Debris mantle regolith is defined as the soil, together with all unconsolidated, oxidised or reduced, texturally uniform or contrasting, and stratified surface sediments of residual, gravitational, fluvial or aeolian origin occurring individually or in some combination. Grades II to VI may exist in the debris mantle regolith.

Variations in regolith type and thickness have implications for understanding both the geomorphic history (Pearce, Phillips and Campbell, 1983) and the inherent properties of the developing soil.

Eggleston (1989) noted a dominant radial organisation of deposits and soil pattern on three fans studied in the Cass Basin, New Zealand, with no differentiation with respect to soil texture from fan head to fan toe. Tonkin and Eggleston (1991) developed these findings further to produce two deposition models that explained and described regolith distribution on fans dominated by debris flow or alluvial processes. Figure 3.1 shows the strongest radial soil pattern to be associated with debris flow transport, whereas with the alternating model soils are distributed more laterally in zones down the fan. In both models shifting intersection point deposition controls soil distribution laterally and radially.

Figure 3.1. Models of the deposition and distribution of regolith on alluvial and debris flow dominated fan based on sedimentological studies of fans (adopted from Tonkin and Eggleston, 1991).



3.2 Soil sequence models.

As previously established a relationship exists between the regolith and the soil pattern. It is controlled by spatial and/or temporal state factors (Burns and Tonkin, 1982). Soil stratigraphic techniques are used to determine whether deposition or erosion are progressive or episodic.

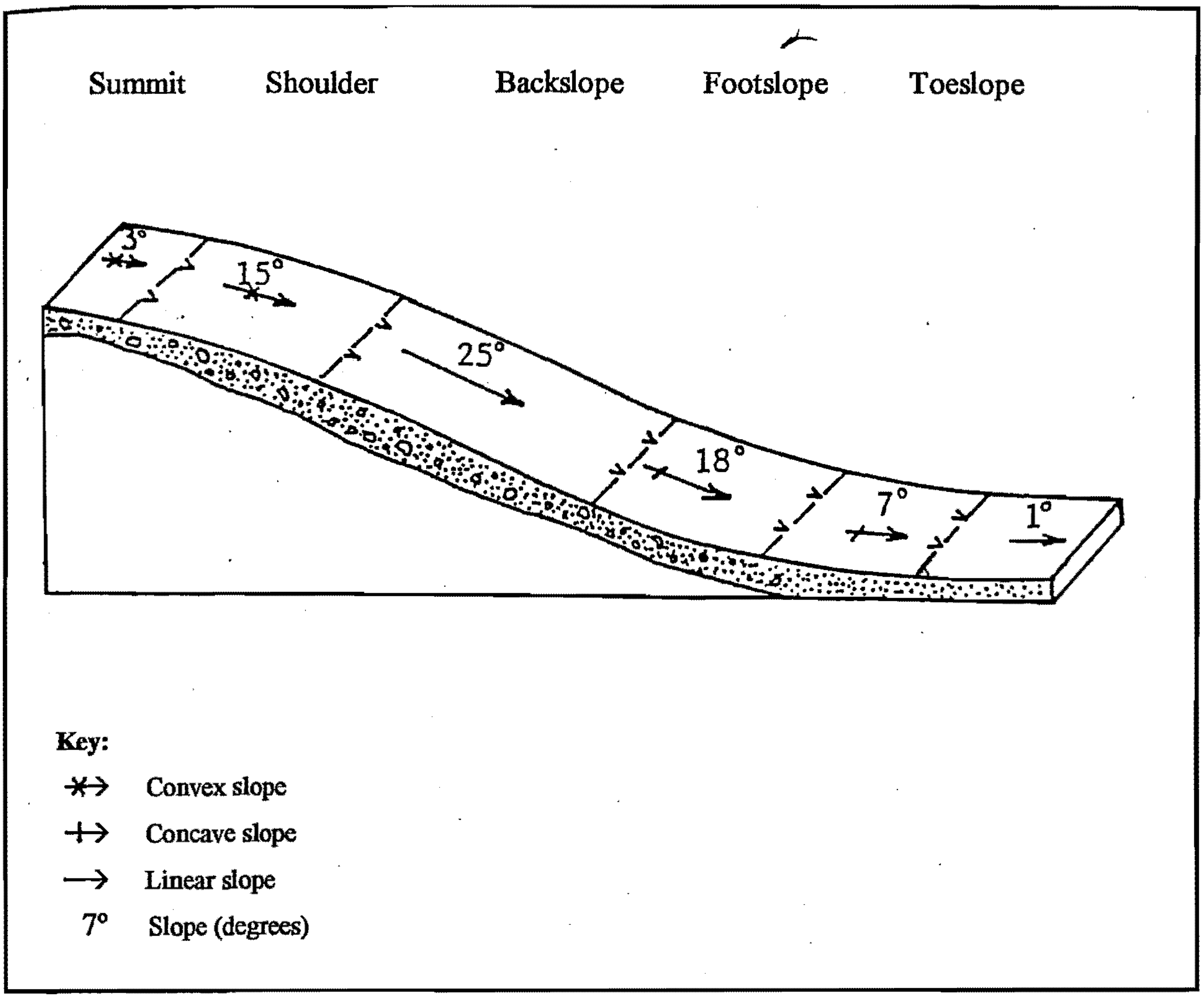
Toposequences and chronosequences are the conceptual models that have been employed to study soil development and distribution on fans, with respect to slope and time respectively.

3.2.1 Toposequences: the soil catena.

The soil catena concept recognises the lateral transfer of solutes through spatially linked soils of a topographic sequence (Jenny, 1941). A model is provided for the development of soils on stable fan surfaces, intergrating geomorphological processes and pedological processes (Tonkin, 1984).

Fan morphometry studies (Bull, 1977 and others), suggest a three dimensional slope variation for fans. That is, the fan slope is unidirectional incorporating lateral and radial components. An adaption of the three dimentional model introduced by Huggett (1975) and used for soil-landform studies of a small watershed by Tonkin (1984) may be more applicable. The fan provides all the requirements for a catena; slope, a hydrological continuum and sufficient stability (i.e. time) for a geochemical gradient to be expressed. Debris flow fans encompass similar features as the Bealey Spur catena illustrated in Figure 3.2.

Figure 3.2. Summarised slope form for the basin showing the main slope units and mean slope angles of the Bealey Spur catena (adopted from Young, 1988).



Stable surfaces may not predominate where there is closley timed episodic fan activity (i.e. surfaces are temporally distributed) and the requirements for a catena will not be met.

3.2.2 Soil chronosequences.

Stevens and Walker (1970) defined a chronosequence as:

> "A sequence of soils developed on similar parent materials and relief under the influence of constant or ineffectively varying climate and biotic factors, whose differences can thus be ascribed to the lapse of differing increments of time since the initiation of soil."

Soils differ in duration of development, moment of inception and cessation. Vreeken (1975) described four types of chronosequence as shown in Table 3.2.

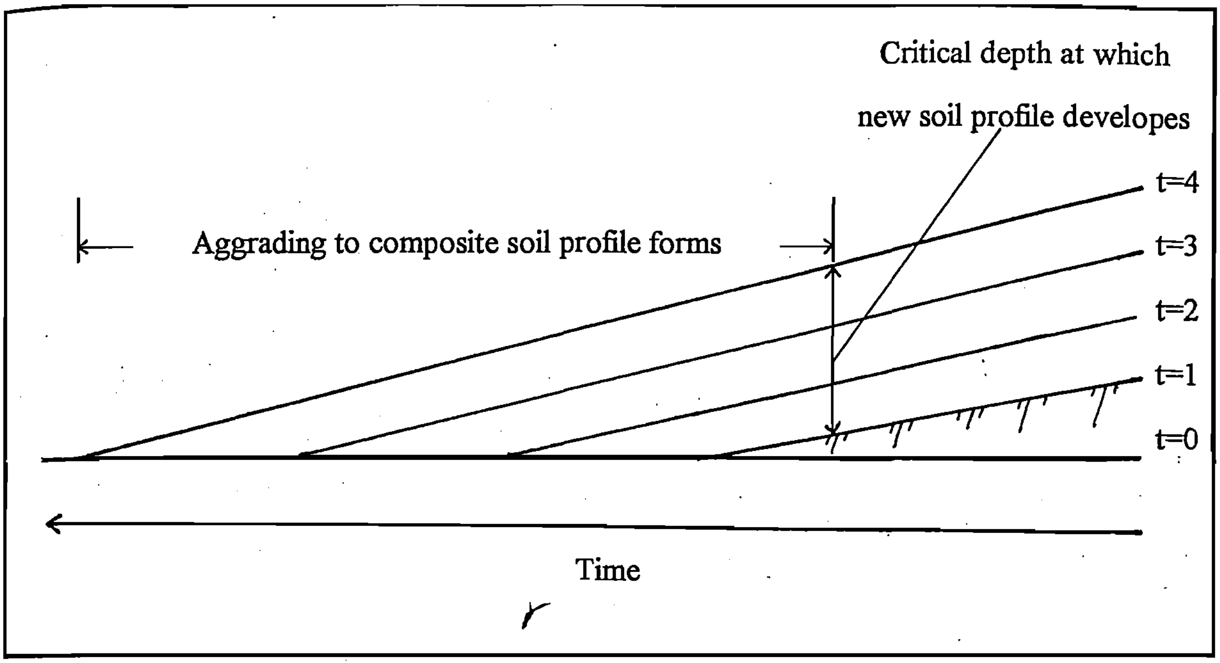
Table 3.2. Principle types of chronosequence (after Veerken, 1975).

Chronosequence	Time zero of soil development	Time of cessation of soil development	Soil history
Post-incisive	Time-transgressive	Isochronous	Partial overlap
Pre-incisive	Isochronous	Time-transgressive	Partial overlap
Fully time-transgressive	Time-transgressive	Time-transgressive	Partial overlap
Fully time-transgressive	Time-transgressive	Time-transgressive	No-overlap

Fan soils examined by Eggleston (1989) were found to be members of a post-incisive, non strict chronosequence (i.e. soils forming at different times and passing through the same stage of development).

With continued deposition the temporal distribution potentially becomes increasingly complex with the occurrence of buried soils. This imposes a time transgressive relationship where soils are subjected to cessation at different times, depending on the type and extent of the active depositional processes. This concept of increased complexity is represented in Figure 3.3.

Figure 3.3. The formation of a time transgressive relationship on temporal fan surfaces.



3.2.3 A soil development sequence.

A soil development sequence was established for soils derived from the debris mantle of Canterbury Suite rocks, under a rainfall of 500 to 2000 mm anually, in the eastern South Island hill and mountain country (see Table 3.3).

Table 3.3. A soil development sequence in the Waimakariri basin (adopted from Cutler, 1977).

Stage of soil development	Horizon sequence	Soil classification
1	A.C	Recent Soils
2	A.BC.C	Recent Soils
3	A.BW.C	Brown Soils
4	A.Bw1.Bw2.C	Brown Soils
5	L,F,H.E.Bw1.Bs.Bw3.C	Brown Soils
6	L,F,H.E.Bs.Bw3.C	Podzols
7	L,F,H.E.Er.Bs.Bw3.C	Podzols

This was further developed to incorporate the influences of slope on soil development (i.e. catenary relationships), illustrated in Table 3.4.

Table 3.4. Changes in horizon development in idealised soil catenas, eastern South Island hill and mountain lands (after Tonkin, Harrison, Whitehouse and Campbell, 1981).

		Soil catena		
Slope position		Summit-shoulder	Backslope	Footslope-toeslope
Stage of	1	C/R	C/R	C/R
soil	2	Ah.C/R	Ah.C/R	Ah.Cg
develop-	3	Ah.Bw.C	Ah.Bw.Bg.C	Ah.Br.Cg
ment	4	H/Ah.E.Bs.C	H/Ah.Bw.Bg.C	H/Ah.Br.Cr
	5	H.E.Bs.C	H.Er.Bsr.Cr	O.Bsr.Cr

Lynn (1987) used soil chemical properties as indices of soil development and soil nutrient status to demonstate soil fertility build up, stability and decline with increased soil development. This approach of encompassing both temporal and state factors into a single model is most appropriate for the assessment of the fan soil pattern and was adopted by Eggleston (1989).

3.3 Soil Stratigraphy and periodicity.

3.3.1 Soil stratigraphy.

Soil stratigraphy allows the chronological ordering of pedological episodes expressed in surfical and buried soils (Gerrard, 1981). The reconstruction of erosional and depositional events can established, using soil stratigraphic techniques applied in conjunction with dating methods (Tonkin, Harrison, Whitehouse and Campbell, 1981).

3.3.1.1 Soil stratigraphic unit.

A number of terms have been proposed as soil stratigraphic units; geomorphic surface (Ruhe, 1956, 1959, Gile, 1975); ground surface (Butler, 1959); geosol (Morrison, 1967, 1978); pedoderm (Brewer, Crook and Speight, 1970; Butler, 1982; Walker, Beckmann and Brewer, 1984).

In New Zealand studies the term geomorphic surface has been used in studies of soil landform relationships (Tonkin, 1984; Eggleston, 1989).

Ruhe (1969) defined a geomorphic surface as a proportion of the land surface comprising either erosional ~~and~~ or depositional elements, having continuity in space and a common time of origin. It may occupy an appreciable part of the landscape and include many lanforms. A geomorphic surface represents a stable surface beneath which soil development has been permitted. Ruhe (1956) delineated geomorphic surfaces by identifying specific soils or soil associations and the soil's pedogenic features related to each geomorphic surface. Similar approaches were taken by Gile (1977), Kesel and Spicer (1985) and Eggleston (1989).

Gile, Hawley and Grossman (1981) defined geomorphic surfaces in terms of genetic landform components, geological age and related pedogenic features. The geomorphic surface provides a "tool" for determining soil age (Peterson, 1981), predicting soil occurrence and describing the physiographic positioning of soils (Eggleston, 1989) and is therefore suitable for identifying the stratigraphy of fan surfaces.

General criteria for recognising individual geomorphic surfaces and dating are summarised by Harrison (1982) and Eggleston (1989).

3.3.2 Soil periodicity.

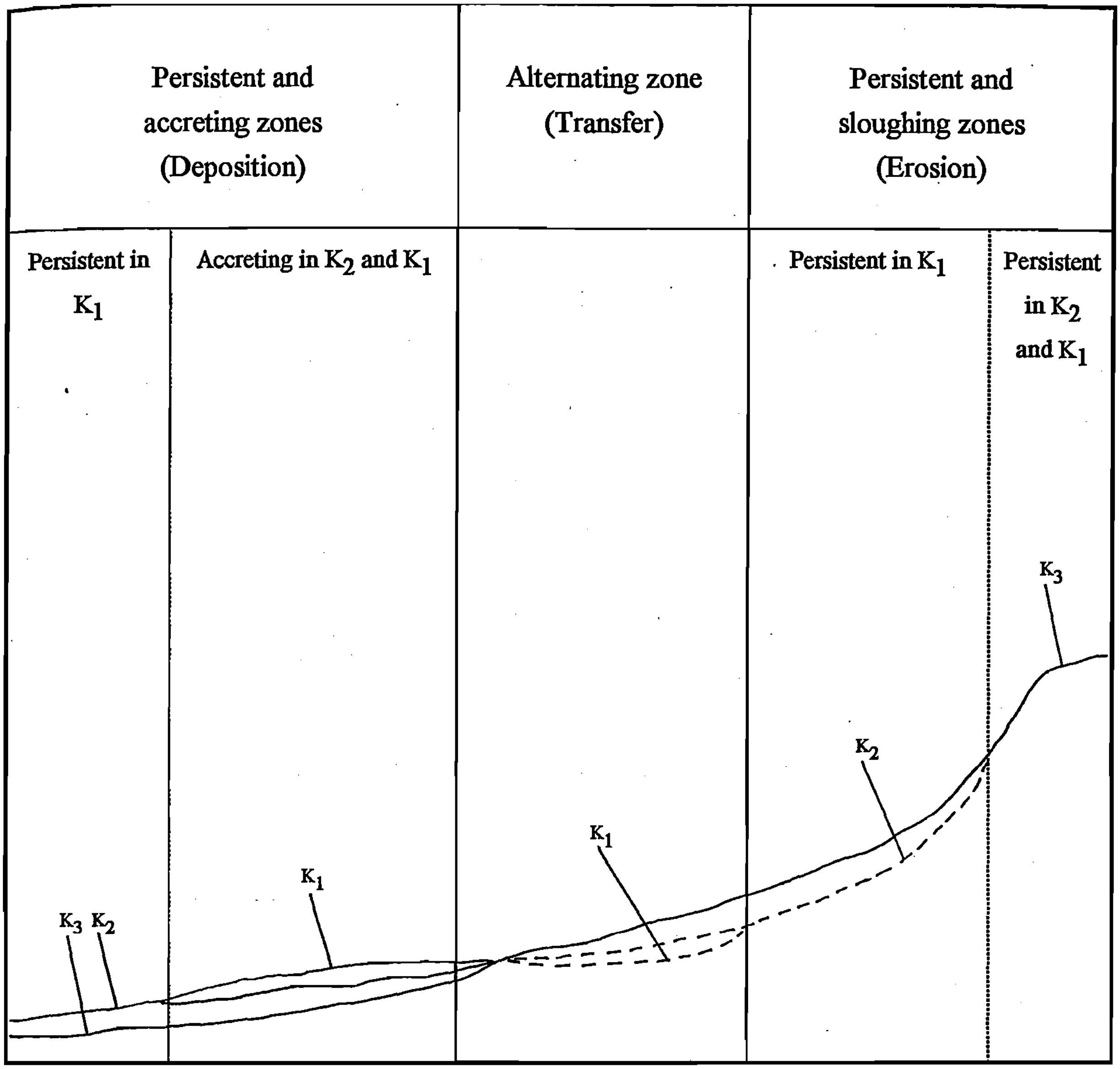
The periodicity model (Butler, 1959, 1982) allows for the examination of the relationship between the soil pattern and the erosional and depositional history of the landscape (Tonkin, 1985).

The model incorporates stable phases when geomorphic surfaces (and associated soils) are formed and phases of instability when geomorphic surfaces are destroyed by erosion or burial the periodicity cycle is regarded as a time unit (a K cycle). Recognition of successive K cycles in the stratigraphic record allows the chronological sequencing of depositional and erosional events (Tonkin, 1985).

Buried soils in the debris mantle regolith provide stratigraphic evidence of periodicity and together with the use of soil dating techniques both relative and absolute surface ages can be established (Eggleston, 1989).

Only part of the land surface can be affected by any particular K cycle resulting in different surfaces being formed as shown in Figure 3.4.

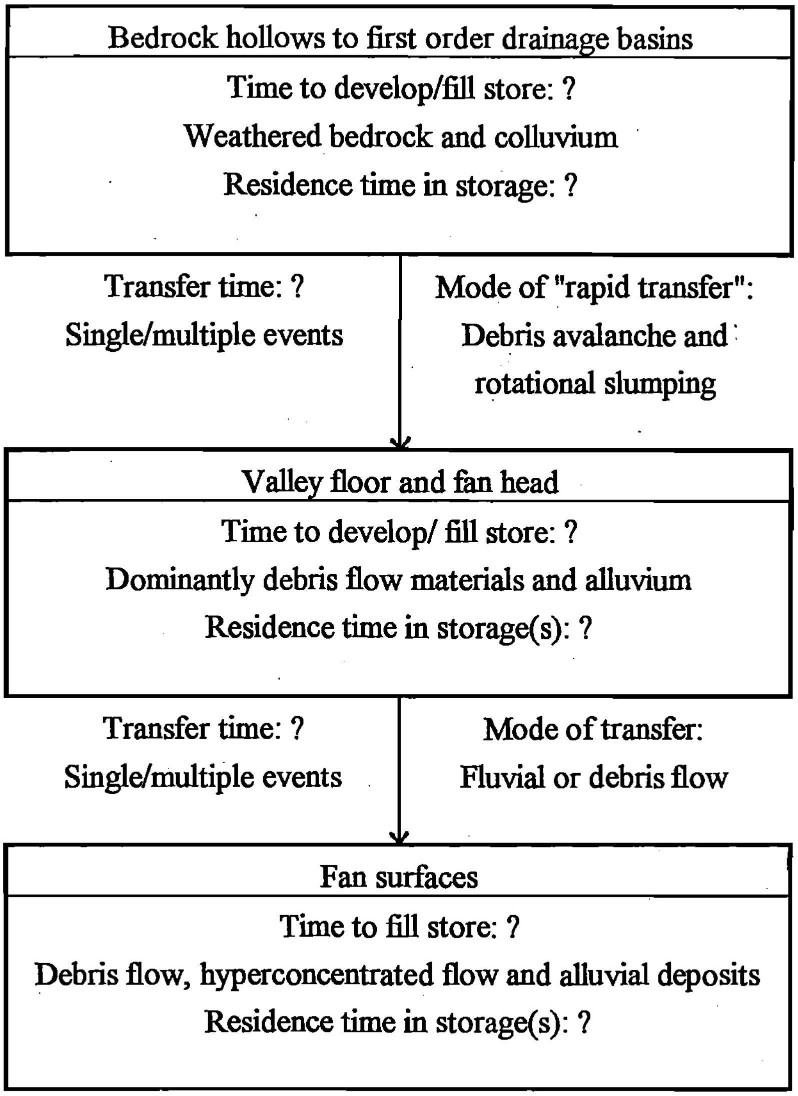
Figure 3.4. The K cycle model as it applies to the fan system, with the relationships between K_1, K_2 and K_3 ground surfaces (geomorphic surfaces) shown (adopted from Butler, 1958, 1982).



A persistent zone exists only where the landsurface is not affected during a period of instability. Erosional and depositional elements of one K cycle occur in an alternating zone; an extensive mosaic of degradational and aggradational phases of geomorphic surfaces (Tonkin *et al.* 1981).

Tonkin and Basher (1991) incorporated the fluvial system model (Schumm, 1977) and the soil periodicity model (Butler, 1958, 1959) to provide a framework for soil landform relationship studies of drainage basins, valley floors, terraces and fans in the central Southern Alps, South Island. An adapted version for the fan system is shown in Figure 3.5.

Figure 3.5. Fluvial system-erosion/depositional model for the fan system (adopted from Tonkin and Basher, 1991).



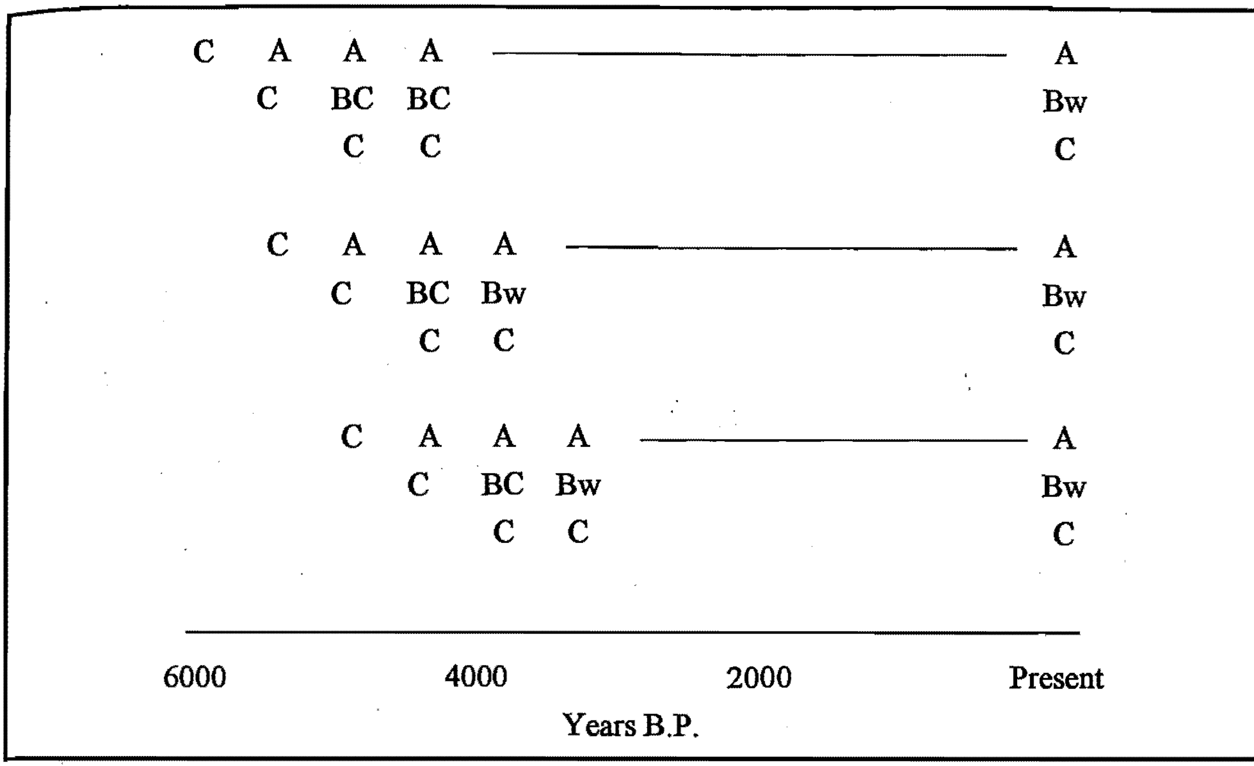
3.3.2.1 Stability: persistent soil profile forms.

Burns and Tonkin (1982) suggest that where the stable phase of a K cycle is of sufficient duration soil variability will be primarily controlled by spatial factors related to topography and a soil catenary array will be recognised.

Over long periods of stability soil development tends towards a steady state (Yaalon, 1971). Soils with strongly similar morphological properties may exist on geomorphic surfaces of varying age or on similarily aged surfaces in contrasting soil-forming environments (Tonkin and Burns, 1991).

Soil profiles easily distinguished at early stages of development lose their "sensitivity", becoming morphologically inseparable with time. Tonkin and Basher (1991) found this to be the case with Brown Soils (Dystrochrepts) in the eastern front ranges of the South Island, New Zealand. The time periods for development to a steady state are given in Figure 3.6.

Figure 3.6. Hypothetical development of persistent soil profile forms.



Similar soil profiles are only distinguished by their chemical and mineralogical properties, as Mollisols or Dystrochrepts.

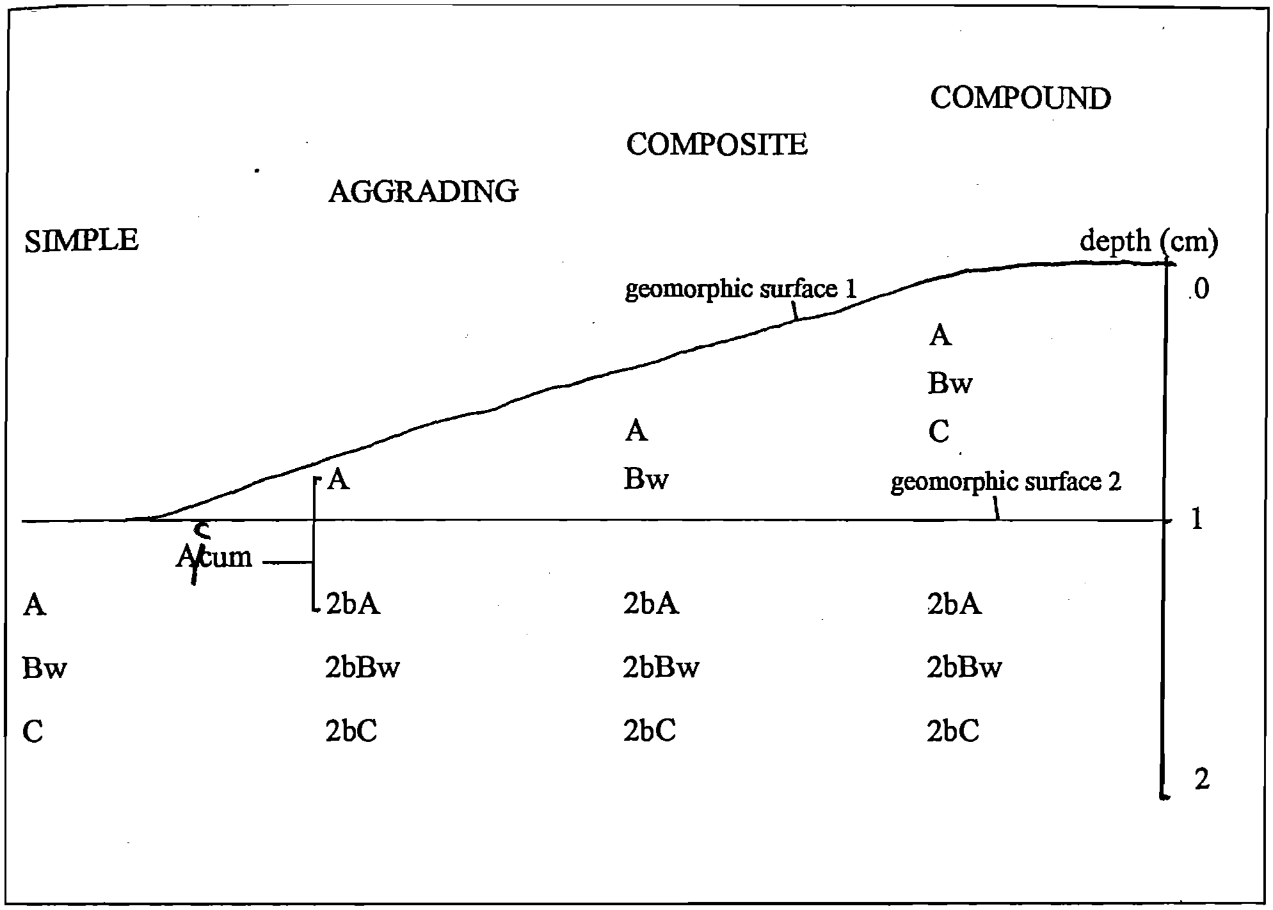
Tonkin and Eggleston (1991) had similar findings for fans in intermontane basins, central Canterbury, South Island, with the evolution of soils toward persistent soil forms (Dystrochrepts), giving the illusion of a less complex soil stratigraphy on older fan segments than younger segments.

3.3.2.2 Instability: soil profile forms.

Slope stability allows the accumulation of the colluvial store and the development of the soil mantle. However as the threshold conditions are approached the factor of safety decreases. Exceeding the threshold results in single or multiple events (the unstable phase of Butler's K cycle model). The onset of an unstable phase creates new erosional and depositional surfaces which may be transitory until a new stability is achieved. During this interval a complex array of simple, compound, composite and aggrading soil profile forms may develop obscuring or destroying soil catenary gradients. If the time interval between periods of stability and instability has been sufficient several K cycles may be represented by the development of a distinctive soil mantle on each of the erosional or depositional surfaces
(Tonkin and Basher, 1991).

Bos and Sevink (1975) proposed three types of soil profile form (simple, compound and complex) to represent the effects of landform instability and pedogenesis, namely the occurence of "poly" and "mono" pedomorphic soils. Eggleston (1989) used a similar nomenclature which incorporated the ideas of Morrison (1978). The relationship between these simple, aggrading, composite and compound soil profile forms is represented in Figure 3.7.

Figure 3.7. A model for soil profile forms in an unstable depositional/erosional environment (adopted from Eggleston, 1989).



Soil profile forms were defined accordingly.

Simple profile form.

A profile with a single horizon sequum (unisequal), overlying a C horizon, developed in sedimentary bodies that have been deposited either rapidly in a single event or slowly without prolonged breaks in sedimentation.

Aggrading profile form.

A single horizon sequum overlying a C horizon, but characterized by a thickened A horizon which has resulted from gradual aggradation or addition of sedimentary bodies of insufficient thickness to form a separate soil horizon sequum. There was no clear distinction between the upper boundary of the buried soil and surface horizon.

Composite profile form.

These occurred where the horizonation is multisequal and each sequum was sufficiently thin that 'welding' (soil welding of Ruhe and Olsen, 1980) of soil morphological, chemical and physical features would ultimately obscure the soil stratigraphy and result in complicated profile depth trends.

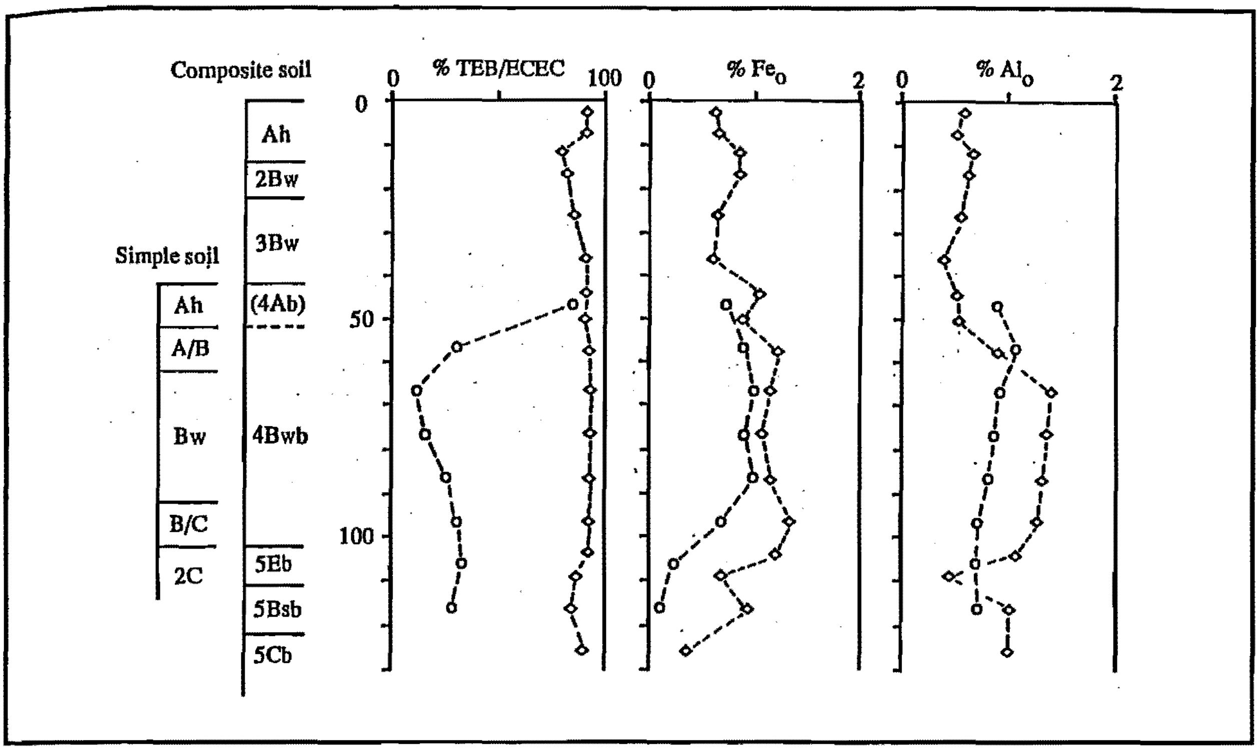
Compound profile form.

Horizonation was bisequal with the lower sequum being initially formed as a surface soil prior to burial. The overlying sedimentary layer and buried soil sequum were sufficiently thick that eventual pedogenic "welding" of the two is unlikely to obscure the buried soil.

Diagenetic change in multisequal soils.

Diagenesis is a feature of multisequal soils, dominantly composite and aggrading profile forms. Ruhe and Olsen (1980) noted this through the welding of soils. Commonly soil chemical properties are altered and hence soil nutrient status may be affected as would the chemical signature which helps establish relative soil development sequences. However Tonkin and Eggleston (1991) found it possible to recognise the buried equivalents of simple soil profile forms (formed in loess) using some soil chemical properties. This is illustrated in Figure 3.8, where diagenetic change is not reflected by all chemical properties.

Figure 3.8. The comparison of a simple soil profile and its' stratigraphically equivalent composite soil profile (after Tonkin and Eggleston, 1991).



3.3.2.3 Periodicity and fan type.

These complex aspects of soil development (a key feature of unstable K cycle phases) are best illustrated in the alternating (transfer) and depositional (piedmont) zones of the K cycle and fluvial system models repectively (Tonkin and Basher, 1991).

Eggleston (1989) found soil profile forms associated with instability to be a feature of all the fans in his study. The debris flow fan possessed the oldest soils of the three fan types (debris flow, alluvial and composite). Compound and composite soil profile forms dominated, with only a few aggrading soils present. In contrast the alluvial fan was composed of thinner layers of debris mantle regolith. As a consequence multisequal soils dominated and were less clearly defined.

3.4. Soil distribution and development.

Knowledge of soil development and the factors determining soil patterns is necessary for the prediction of soil properties, understanding soil nutrient availability, determining soil attributes affecting land management and evaluating land use potential (Lynn, 1987).

This section utilises previous studies to examine soil distribution and development, primarily features concerning Holocene age fans.

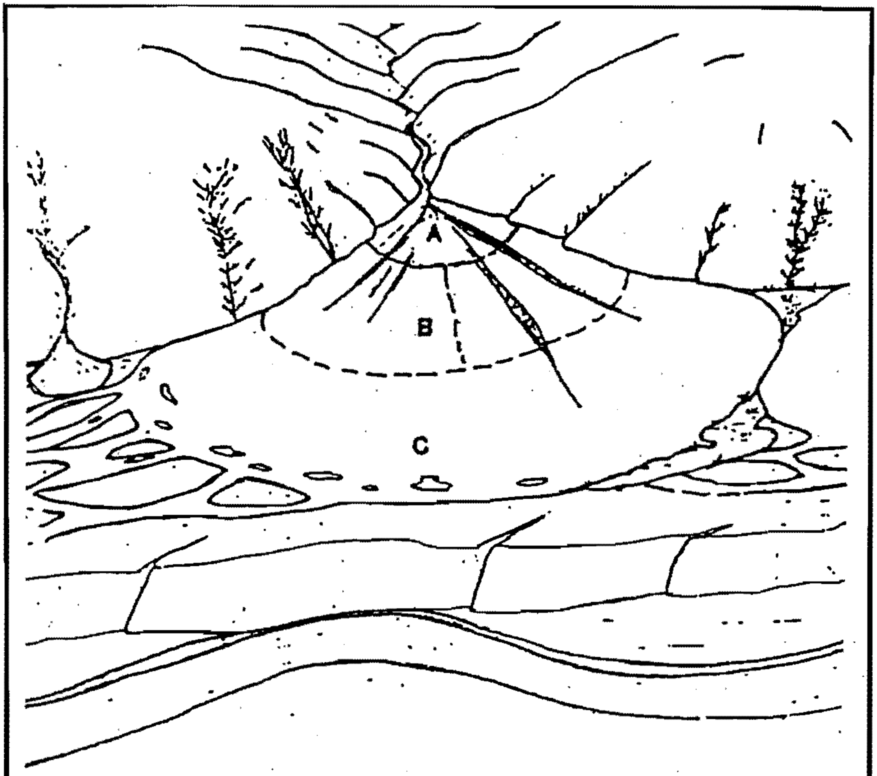
Literature on soil landform relationships, especially fan landforms is scarce. Identified are the implications of climatic environment on soil distribution, morphological and chemical pathways of development and comparitive rates of soil development.

3.4.1 Soil distribution and development on arid and semi-arid fans.

McCraw (1968) outlined a soil pattern model for simple, alluvial fans formed predominantly from schist in the semi-arid Central Otago region. The pattern consisted of three textural zones, with soils becoming increasingly finer down fan as illustrated in Figure 3.9.

Three broad groups of soils were identified according to the stage of soil development. They ranged from soils with little or no profile development, possibly with a weak A and a BC horizon, through soils with compact olive brown subsoils and a weak Bt horizon, to soils with a leached A horizons and a strongly developed Bt horizon.

Figure 3.9. Soil distribution model for Central Otago fans, South Island, New Zealand (after McCraw, 1968).



A Fan head: shallow, coarse textured soils

B Mid fan: coarse textured and fine textured soils

C Fan toe: fine textured soils

With development soil pH decreased (6.0-7.0 to 5.5-6.0), as did percent base saturation (100 to 40) and acid extractable phosphorus (25 to 11 mg/100 g) (New Zealand Soil Bureau, 1967).

The influences of fan stream entrenchment and deposition on soil development are shown in Table 3.5.

Table 3.5. The effect of entrenchment on soil distribution and development (adopted from McCraw, 1968).

Degree of entrenchment	Occurrence of least developed soils
No entrenchment	Fan head
Development of fan head trench	Mid fan
Fan stream entrenched nearly full length of fan	Fan toe

Recent studies (Bull, 1977; Eggleston, 1991; Tonkin and Eggleston, 1991) suggest the redistribution of fan sediments down fan resulting from channel incision, diminishes the contrast in soil/sediment texture between fan head and fan toe.

McCraw (1968) also noted the addition of loess to fan surfaces. The loess ranged in thickness from a few centimetres to several metres, wholly or partially mantling fan surfaces. Well developed soil profiles were evident with several buried soils marking pauses in loess accumulation. On reactivated fans, remnants of the loess soils survived as "islands" amongst coarse textured soils developed in alluvium.

Fan surfaces may be masked by aeolian accumulation (Lynn and Tonkin, 1985), with the presence of loess itself representing a hiatus in fan activity or local deposition as observed by Wasson (1977b) on the Derwent fans, Tasmania.

3.4.2 Soil distribution and development on humid and tropical fans.

Pleistocene fans in the humid setting of the Darjeeling Himalayas displayed greatest pedological development in the mid fan region, with development moderate in the fan head and minimal in the fan toe.

Modes of deposition included stream floods (similar to the sheet floods described by Wasson, 1977b), stream action and mass movements. Fan sediments consisted of coarse grained, poorly sorted sediments decreasing in bed thickness down fan, similar to the fans described by McCraw (1968).

Fluvial (stream flow) action and stream floods dominated the mid fan zone. Here the slope varied between 15 and 30 degrees and soils were formed in sandy and silty sediments.

The pH ranged from ~6.0 (at the surface) to between 6.0-6.5 (at 40-60 centimetres depth) and 5.7-6.0 (at 60-100 centimetres depth) for fan head and mid fan soils, indicating an enriched B horizon (Basu and Sarkar, 1990). Values for pH in the fan toe were ~6.0 and uniform with depth. Leaching in the mid fan was attributed to a decrease in slope accompanied by high precipitation. As a consequence B horizons were darkened by the translocation of soil organic matter. High cation exchange capacity values in the mid and upper fan soils reflected the greater amounts of organic matter present and a predominance of kaolinite clay minerals (Basu and Sarkar, 1990).

Soil-geomorphic relationships on alluvial fans in the Rio General Valley, Costa Rica (Kesel and Spicer, 1985) showed uplift of the bordering mountain ranges to be the major age control over geomorphic surfaces and associated soils. Older more developed soils occupied the higher surfaces with progressively younger soils being associated with the lower surfaces.

Geomorphic surface ages were derived from extrapolation of sediment rates, solum development and the rate of channel incision based on two radiocarbon dates.

This soil sequence represented a chronological array of catenas. It was used to establish the stage and rate of soil development in a humid environment. The general characteristics of geomorphic surfaces and associated soils are given in Table 3.6.

Table 3.6. Selected characteristics of geomorphic surfaces and associated soils (after Kesel and Spicer, 1985).

Geomorphic surface	**1**	**2**	**3**
Estimated age (years)	<100	~7000	45 000-65 000
Horizon sequence	A.C.2C	A.Bt.C	A.B.C
Depth to C horizon (centimetres)	24	145	242
pH range	5.5-5.7	4.9-5.7	4.7-5.6
Soil taxonomy (Soil Survey Staff, 1975)	Entisols	Alfisols	Oxisols

The youngest soils of the braided floodplain possessed well defined A Horizons below which were sedimentary layers of differing grain size representing a shifting braided stream environment. Intermediate aged soils had a well expressed argillic horizon and were dominated by kaolinite clays. Clay distribution in the Bt horizon was irregular representative of alternate periods of deposition and stability (Kesel and Spicer, 1985). There was however no evidence of buried soils reflecting the rapid and intense weathering of the humid environment.

3.4.3 Soil distribution and development on temperate fans.

A succession of inset fans. comprising the lower Waimakariri floodplain, Canterbury, New Zealand, were studied by Basher, Hicks, McSaveney and Whitehouse (1988). Four periods of fan aggradation and degradation, decreasing in age successively down the floodplain were recognised. The soils associated with the different aged surfaces are given in Table 3.7.

Table 3.7. Characteristics of the four fan surfaces and soils of the Waimakariri floodplain (Suggate, 1958; Cox and Mead, 1963; Basher *et al.* 1981; Hewitt, 1992).

Soil age group	Regolith origin	Soil classification (Hewitt, 1992)	Soil age (years B.P.)
Lismore	Stony gravels overlain by thin loess	Pallic Soils	25 000-18 000
Templeton	Reworked gravels, fines and peats	Imature Pallic Soils	10 000-3000
Waimakariri	Recent alluvium with wide textural range	Recent Soils	2400-700
Selwyn	Sediments from floods and channel migration	Recent Soils	<300

Eggleston (1989) found soil distribution to be related to patterns of surface style (surface form), sedimentary deposition and geomorphic surface distribution.

All three fans studied were controlled by temporal state factors, with spatial controls secondary. The presence of soils and buried soils indicated alternating periods of activity and stability. Geomorphic surfaces and their associated soils were ordered chronologically as were the fan types; alluvial-composite-debris flow, young to old.

The soil development sequence representative of the soils observed followed that of Cutler (1977), described in chapter 3.3.3 and Lynn (1987) incorporating both temporal and spatial factors.

A major hiatus in the stratigraphic record was indicated on the debris flow fan with the formation of strongly developed podzol soils (Katrine soils), described in Table 3.8.

Table 3.8. Selected characteristics of geomorphic surfaces and associated soils (Eggleston, 1989).

Geomorphic surface	1	2	3	4
Associated soils	Tasman	Snowgrass	Cass	Katrine
Horizon sequence	Ah.C Ah.Ac.C	A.BC.C Ah.Br.Cr	A.Bw.C	Ah.E.Bs.Bw.C
Depth to C horizon (cm)	12	65	50	60
pH range	6.0-5.6	6.0	5.1-5.6	5.1-5.7
Percent base saturation	98-46	99-97	61-7	59-5
Soil classification (Hewitt, 1992)	Recent Soils	Brown Soils	Brown Soils	Podzols

The greatest array of soils ages was found on the debris flow fan. Older soils were highly leached and weathered with lower pH and base saturation values than the younger soils.

Catenary effects were evident in the soil associated with geomorphic surface 2. Very high exchangable calcium values reflected the transport of nutrients downslope by throughflow to the central fan toe region (equivalent to the illuvial toeslope of the Bealey Spur catena described by Young (1988).

CHAPTER 4
BULLOCK CREEK CASE STUDY

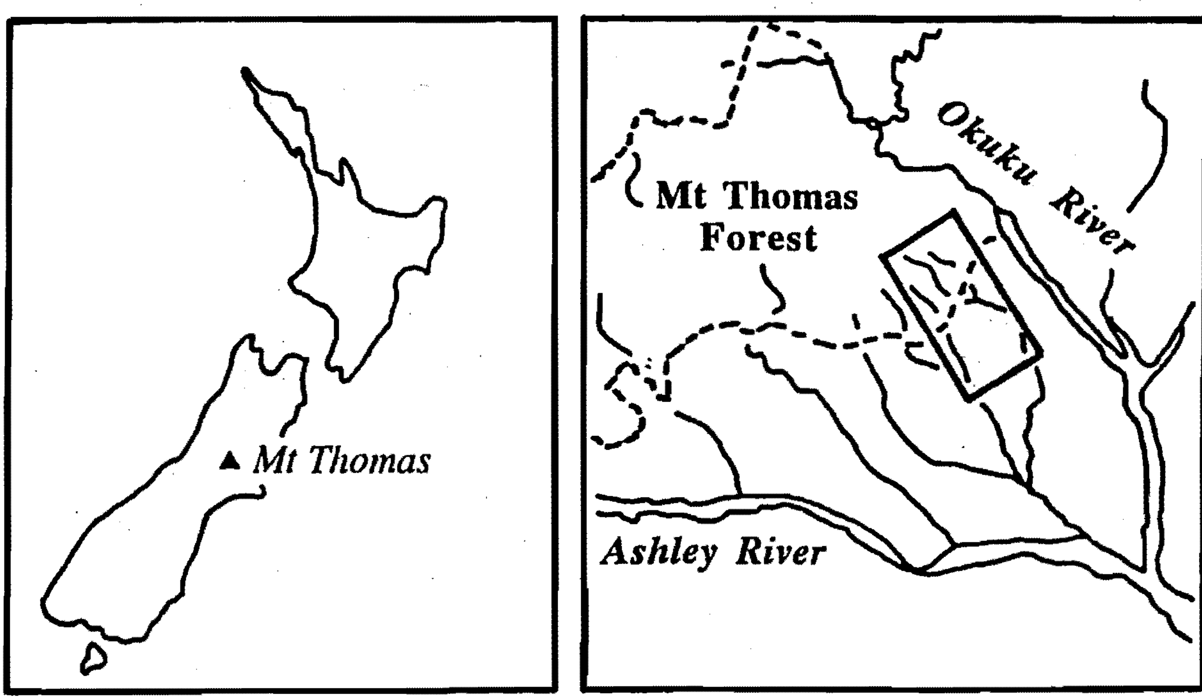
CHAPTER 4.0 BULLOCK CREEK CASE STUDY.

4.1 Physical environment.

4.1.1 Regional setting.

The Bullock Creek drainage basins and fan are situated in the Mount Thomas Forest and adjacent farmland (Figure 4.1) on the south-eastern flank of Mount Thomas.

Figure 4.1. Location map of Bullock Creek fan (adopted from Pierson, 1980b).



4.1.2 Geology.

Mount Thomas is on the southeast edge of an upfaulted mountain block composed of thick-bedded, well jointed greywacke sandstone and tectonically sheared argillite of the Triassic Torlesse Group. Tertiary sedimentary rocks are faulted against this block and are overlain by Pleistocene sediments of alluvial and mass movement origin (New Zealand Geological Survey, 1964; Pierson, 1980b). Late Pleistocene loess covers much of the lower and rolling hills.

4.1.3 Climate.

New Zealand is situated in the mid latitude westerly zone, where climate is dominated by the passage of successive anticyclones and depressions (New Zealand Meterological Service, 1983). The following climatic data were collected 40 kilometres northeast of Mount Thomas at the Ashley Forest station and are cited from New Zealand Soil Bureau (1967) and New Zealand Meterological Service (1983).

4.1.3.1 Precipitation.

At Mount Thomas the mean annual rainfall is 1100 millimetres. It is wettest in the autumn and driest in the spring. Autumn has the lowest number of rain days, which coupled with the highest rainfall, is responsible for the occurrence of long duration rainstorm events consisting of occassional intense rainfall bursts. Such an event was described by Pierson (1980b) in April of 1978. On the 14th and 15th a small storm delivered 15 millimetres. Within 24 hours a further storm produced 140 millimetres to Mount Thomas in less than two days. On April the 19th 170 millimetres more rain fell steadily. During this period debris flow activity began.

Snowfall occurs on average twice a year and may remain for up to two weeks.

4.1.3.2 Temperature.

Temperatures are more extreme in the foot hills compared with those towards the coast. The mean annual temperature is 11.0 degrees celsius, ranging from a mean winter low of 6.2 degrees celsius to a mean summer high of 16.1 degrees celsius.

4.1.3.3 Frost.

Ground frosts are most common in the winter months of June, July and August. The average yearly incidence of frosts is 49 days. Ground freezing occurs more frequently at higher altitudes and within the deeply incised gullies.

4.1.3.4 Wind.

Summer winds are dominantly strong northwesterlies, of low humidity and high evaporative demand. Southwesterlies are more common in the autumn and winter bringing with them the larger rainfall events.

4.1.4 Landuse and Vegetation.

Mount Thomas was being farmed in 1851 and the native woody vegetation was progressively reduced by burning and grazing. In addition large areas of forest were milled with milling opperations ceasing in about 1900. Today the area surrounding the Bullock Creek drainage basins consists mainly of exotic tree species with small remnants of native forest in gullies and along gully sides.

Above the treeline fescue and snow tussock dominate, with scattered shrubs of Dracophyllum, Cassinia, Hebe and Coprosma are also present.

Corsican pine (*Pinus nigra* var. *laricio*) and Bishop pine (*Pinus muricata*) are the principal species growing above 650 metres. They were planted to reduce erosion and mass movement.

There are 1300 hectares of exotic trees, dominantly *Pinus radiata* and Douglas fir (*Pseudotsuga menziessi*) planted on the lower, gentle slopes of Mount Thomas.

Willow, gorse, lotus and New Zealand broom inhabit the more recently active valley floor and fan head surfaces.

The farmland consists of mainly fescue, ryegrass and clover pastures. Rushes occupy the swampy areas, with cabbage trees (*Cordyline australis*), kanuka (*Leptospermum ericoides*), matagouri (*Discaria toumatou*), and gorse (*Ulex europaeus*) inhabiting the uncultivated areas.

4.2 Drainage basin and fan character.

4.2.1 Geomorphic setting.

The fluvial system model (Schumm, 1977) has been employed to assess the fan system (refer figure 2.1 in chapter 2.2).

Three deeply incised, headward eroding drainage basins comprise the sediment production zone. Plate 4.1 shows the presently active middle drainage basin. These feed the Bullock Creek and Mount Thomas streams through the transfer zone, directing deposition to the deposition zone (the fan surfaces).

Erosion and sediment production processes are dominated by debris avalanches on bedrock faces and loose rock rubble, and rotational slumping of unstable debris mantle and debris mantle regolith. Large concentric tension cracks line the rim of the middle drainage basin.

Sediments are transfered from the drainage basins primarily by debris flow processes. Plate 4.2 shows a small debris flow lobe deposited in the upper valley floor.

Plate 4.1. The middle drainage basin, the largest sediment source in the Bullock Creek fan system, Mount Thomas.

Plate 4.2. Small debris flow lobe in the upper valley floor.

Fluvial processes transfer sediments to a lesser extent, playing a greater role in the reworking of sediments in the valley floor and the fan head region (referred to by Pierson (1980b) as the upper active segment of a confined alluvial fan).

Extending from the valley floor is an alluvial fan. Pierson (1980b) observed the fan to be inactive and of an unknown age. Distal fan margins were lobate indicating possible debris flow activity.

4.2.2 Geomorphic History.

Pierson (1980b) provides an historic account of debris flow activity and fan building.

Although erosion may have accelerated with the removal of vegetation in the mid to late 1800's adjacent piedmonts containing oxidised gravels of dominantly debris flow origin are evidence of geomorphic activity over the past tens of thousands of years. More recent episodes of fan activity have dissected the older deposits and the resulting fan deposits overlie and interfinger their older counterparts.

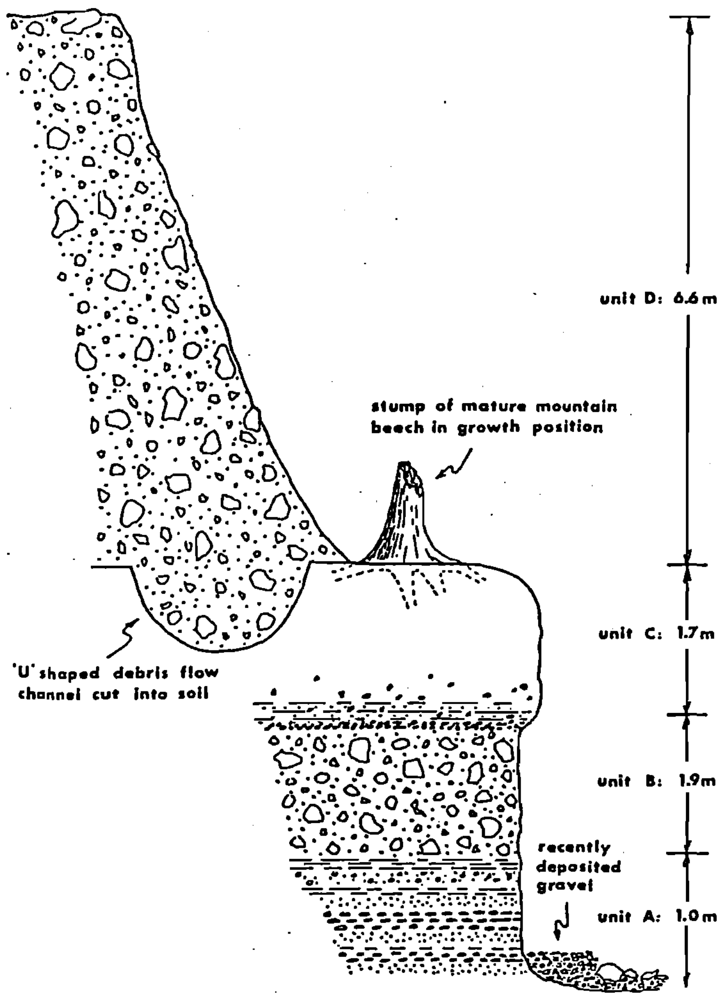
A stratigraphic section exposed by stream entrenchment in the upper valley floor revealed two major episodes of aggradation (see Figure 4.3).

Forest Service records and residents' memories of debris flow episodes correlate well with large rainstorms in 1923, 1941, 1945, 1951, at least once in the 1960's, 1971, 1972, 1973 and 1978 (Pierson 1980b). More frequent activity in recent times was attributed to wetter winters in the 1970's or closer observation by the Forest Service since 1969. Another suggested reason was the clustering of events behind major events which had effectively placed the system out of equilibrium.

Since 1923 the middle catchment has doubled in size, with the head of the valley floor aggrading more than 15 metres. Headward erosion and the appearance of large conical tension cracks around the rims of the drainage basin have been augmented by an earthquake in 1948. The tension cracks have deepened nearly 5 metres in the last 12 years (Marty Thompson, personal communication). The western drainage basin (the main active drainage basin in 1923) is currently less active.

Debris flows observed by Pierson (1980b) in April 1978 consisted of surges of viscous flow separated by intervals of "slurry" flow. The largest surge measured 3 metres in height.

Figure 4.3. Stratigraphic section in the upper valley floor of the Bullock creek fan system (after Pierson, 1980b).



Key:

unit A: Oxidised, bedded, sorted sand and gravel (fluvial deposit).

unit B: Oxidised diamicton (debris flow deposit), fluvial reworking in the top 20 centimetres).

unit C: Silt (loess), with well developed soil profile.

unit D: Unoxidised diamicton (debris flow deposits), featuring indistinct parallel layers 1.0 to 1.5 metres thick.

Stones and boulders were sorted laterally out of the flow forming well sorted levees along the flow margins. In the valley floor debris flows followed existing stream channels, which were susequently incised up to 10 metres. On the lower fan surfaces more fluid debris flows spread out as sheets closely paralleling the old topography. Lithological and environmental factors favouring slope erosion and debris flow initiation in the drainage basins included:

1. Bedrock comprising crushed, brecciated and highly sheared Torlesse sndstones and siltstones (see Plate 4.3).
2. Narrow, steep sided (greater than 25 degree slopes) valley slopes propagating surface instability within the shallow (less than 50 centimetres deep) Stony Brown Soils, Ranker Recent Soils and Stony Orthic Raw Soils present[2]
3. Deforestation by milling and burning prior to 1900.
4. Annual rainfalls of 1100 millimetres with occassional intense rainfall bursts in long duration storms such as the storm documented by Pierson (1980b) in April 1978.

Plate 4.3. Brecciated and highly sheared Torlesse siltstone in the Bullock Creek drainage basin.

Other characteristics observed by Pierson (1980b) are given in Table 4.1.

[2] Hewitt (1992).

Table 4.1. Comparison of selected flow characteristics for debris flow and hyperconcentrated flow types (adopted from Pierson, 1980b).

Flow type	**Debris flow**	**Hyperconcentrated flow**
Flow density (T/m^3)	~ 2.0	~ 1.5
Velocity (m/s)	~ 4.0	~ 1.5
% Solids (by weight)	~ 80	~ 60
Particle size distribution (%)	gravel 70 sand 20 silt 6 clay 4	gravel 20 sand 55 silt 15 clay 10
Sorting	very poor	poor to moderate
Appearance of flow	laminar	turbulent
Location of coarse load	throughout the flow depth	segregated as bedload

4.2.3 Soil information.

Information on the soils of Bullock Creek fan is limited and general. New Zealand Soil Bureau (1967) provided a soil map (scale 1:126 720) and descriptions of typic profiles for the soils encountered.

The Bullock Creek fan is shown to be dominated by the Okuku silt loam, easy rolling phase and the Haylands silt loam. Soils of the Coopers Creek Complex occupy a small portion of the left hand corner of the fan.

The Okuku silt loam, easy rolling phase is derived from weathered loess and gravelly alluvium (overlying the Kowai gravels), often consisting of interbedded sands, silts and clays. It occurs on more gentle slopes than the Okuku silt loam and is subsequently more mottled in the subsoil. The soil is imperfectly drained and subjected to seasonal waterlogging. Topsoil depth is variable depending on the extent of surface erosion. The soil is highly leached and has low natural fertility.

Haylands silt loam is found on undulating to flat land often in association with Okuku silt loam, easy rolling phase. The soil is formed on alluvium derived from the erosion of loess and conglomerate beds. It is moderately leached, very low in phosphorus and slow draining. The topsoil is of moderate depth and the lower soil horizons are reduced.

Soils of the Coopers Creek Complex occupy depressions. They are derived from admixtures of greywacke, Tertiary sediments and loess washed from the existing soil mantle. These soils are waterlogged for long periods of the year and consequently have reduced subsoil colours.

Detailed soil profile descriptions are given in New Zealand Soil Bureau, (1967).

CHAPTER 5
METHODS

CHAPTER 5.0 METHODS.

5.1 Field studies.

5.1.1 Research phase.

5.1.1.1 Objectives.

The primary objectives of the field studies were to identify the dominant state factors influencing the soil pattern and map the distribution of soils. Establishing the distribution of depositional processes, regolith and surface age on the fan was also of importance.

5.1.1.2 Limits.

The main limitations on the survey were cost and time. All observation pits were dug manually which limited the number of observations.

5.1.1.3 Scale.

A detailed survey with an intensity level 2 (Dent and Young, 1981) was chosen for this study. At this level aerial photographs are still used, however the majority of information is obtained from the field. Both simple and compound mapping units were used.

Aerial photographs (scale of 1:10 000 and 1:25 000) were enlarged to provide a base map of 1:5000, from which final maps were produced at a scale of 1:10 000.

5.1.1.4 Reconnaissance.

A reconnaissance survey was undertaken to identify surface form patterns, general soil landform relationships and the key morphological characteristics of soil profile forms. From this a provisional list of soil mapping units and soil profile classes were established using additional information from previous studies.

5.1.2 Mapping phase.

5.1.2.1 Method of survey.

Mapping was carried out using a free survey approach. Surface form, sedimentary form and geomorphic surfaces were mapped in conjunction with the mapping of the soils. Surface form was mapped using aerial photographs followed by field checking. Maps of sedimentary form characteristics and multisequal/unisequal soil distribution were based on soil profile description data. Geomorphic surfaces were identified using soil profile morphological characteristics (described in detail in chapter 6.2.3).

5.1.2.2 Soils.

Objectives of soil mapping.

The major objective of soil mapping was to delineate the landscape (landform), into soil bodies, comprising one or more soil profile class which can be consistently identified by field-determined morphological properties (Tonkin, 1984).

Soil mapping units.

The soil mapping units adopted in this thesis were those defined by Tonkin (1984). Both simple and compound soil mapping units were used; the consociation and the complex respectively.

Field observations.

Density and location criteria for observations followed that of Dent and Young (1981). There were 15 detailed soil profile descriptions made. The remainder of observations were by auger (approximately 200).

Sampling of soils.

Sample sites were chosen to represent the soil profile forms identified on the fan. Six soils were sampled. Samples were taken from each horizon down the profile. Where horizons exceeded 10 centimetres in thickness, 10-15 centimetre sub-samples were taken.

Sampling for carbon date.

The charcoal was removed from the soil profile and retained in a dry plastic container prior to preparation.

5.2 Laboratory studies.

5.2.1 Soil chemical analyses.

5.2.1.1 Choice.

The following chemical analyses were chosen to 1. support interpretations of pedological development based on observations of soil morphology, 2. to identify the presence of buried soils, and 3. to provide soil nutrient status for an array of soils at different stages of development.

1. Soil pH
2. Organic carbon
3. 0.5 M H_2SO_4 soluble phosphorus
4. Acid ammonium oxalate extractable iron and aluminium
5. Cation exchange properties

5.2.1.2 Analytical techniques.

Methods of chemical analysis used are as described by Blakemore, Searle and Daly (1987) unless otherwise stated. All chemical analyses were done in duplicate.

Soil pH.

As for given method. Values for pH were read on a Radiometer 23 pH meter equipped with glass electrodes.

For pH (0.01 M $CaCl_2$) the same procedure was carried out with the exception that 25 ml of 0.01 M $CaCl_2$ solution was substituted for the deionised water.

Organic carbon.

As for given method. Samples were read on the absorption spectrophotometer and the carbon concentration read from a prepared standard curve.

Extractable iron and aluminium.

Extractable iron and aluminium were determined using the acid oxalate extraction shaking method. Iron and aluminium were measured by atomic absorption spectrometry using a lean nitrous oxide-acetylene flame.

H_2SO_4 soluble phosphorus.

As for given method. The developed samples were read on the absorption spectrophotometer and values for H_2SO_4 soluble phosphorus were determined from a prepared standard curve.

Cation exchange properties.

Exchangeable cations and effective cation exchange capacity were determined using the single extraction silver thiourea method (unbuffered 0.01 M AgTU solution).

Exchangeable aluminium and hydrogen were determined using the 1 M KCl exchangeable method.

5.2.2 Carbon date analysis.

5.2.2.1 Pretreatment of charcoal sample.

The method used was as described by Goh and Molloy (1972) with the exception that a 20 g sample of finely ground (250 μm sieve) air-dried charcoal was used and to this 150 ml of 0.1 M $Na_4P_2O_7$: 0.1 M NaOH solution was added for each repeated extraction.

5.2.2.2 Carbon dating.

This was carried out at the dating laboratory, University of Waikato, Hamilton (refer Appendix C).

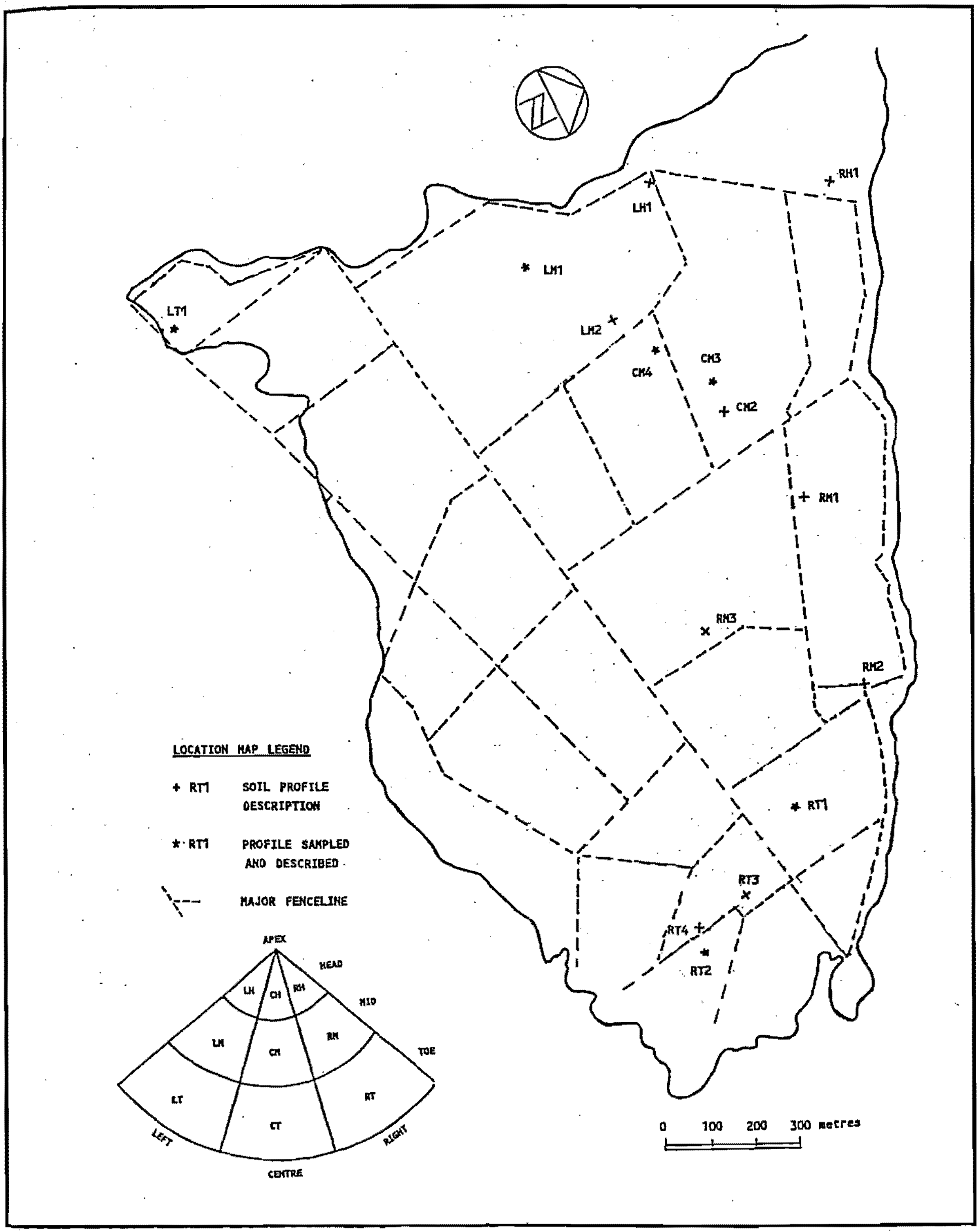
CHAPTER 6
RESULTS

CHAPTER 6.0 RESULTS.

6.1 Introduction.

In this study the fan was divided into nine segments as shown in Figure 6.1. Soil profile description and sample sites were referenced according to the segment they occupied.

Figure 6.1. Site location map.



The field results are presented in three sections; surface form, sedimentary form, and soil stratigraphy. Definitions and descriptions for the maps and results are discussed in each section.

Soil chemical results are presented for each chemical analysis carried out on the selected sample sites shown in Figure 6.1.

6.2 Field results.

6.2.1 Main features of the fan.

The fan covered an area of 300 hectares, mainly farmland with a section of forest occupying the fan head. Slopes ranged from 4 degrees at the fan head, decreasing to 0 degrees at the fan toe. Fan shape was laterally convex and radially concave. The majority of recent activity focussed on the central and right hand side of the fan, with large remnant islands of older surfaces occupying the left hand side. A radial pattern of surface form was evident, extending from the fan apex. Debris flows and other more diluted flows associated with debris flow events dominated fan formation. There was no major stream flow activity observed on the fan. This suggested reworking of surface form occurred during or immediately following debris flow events.

6.2.2 Surface form.

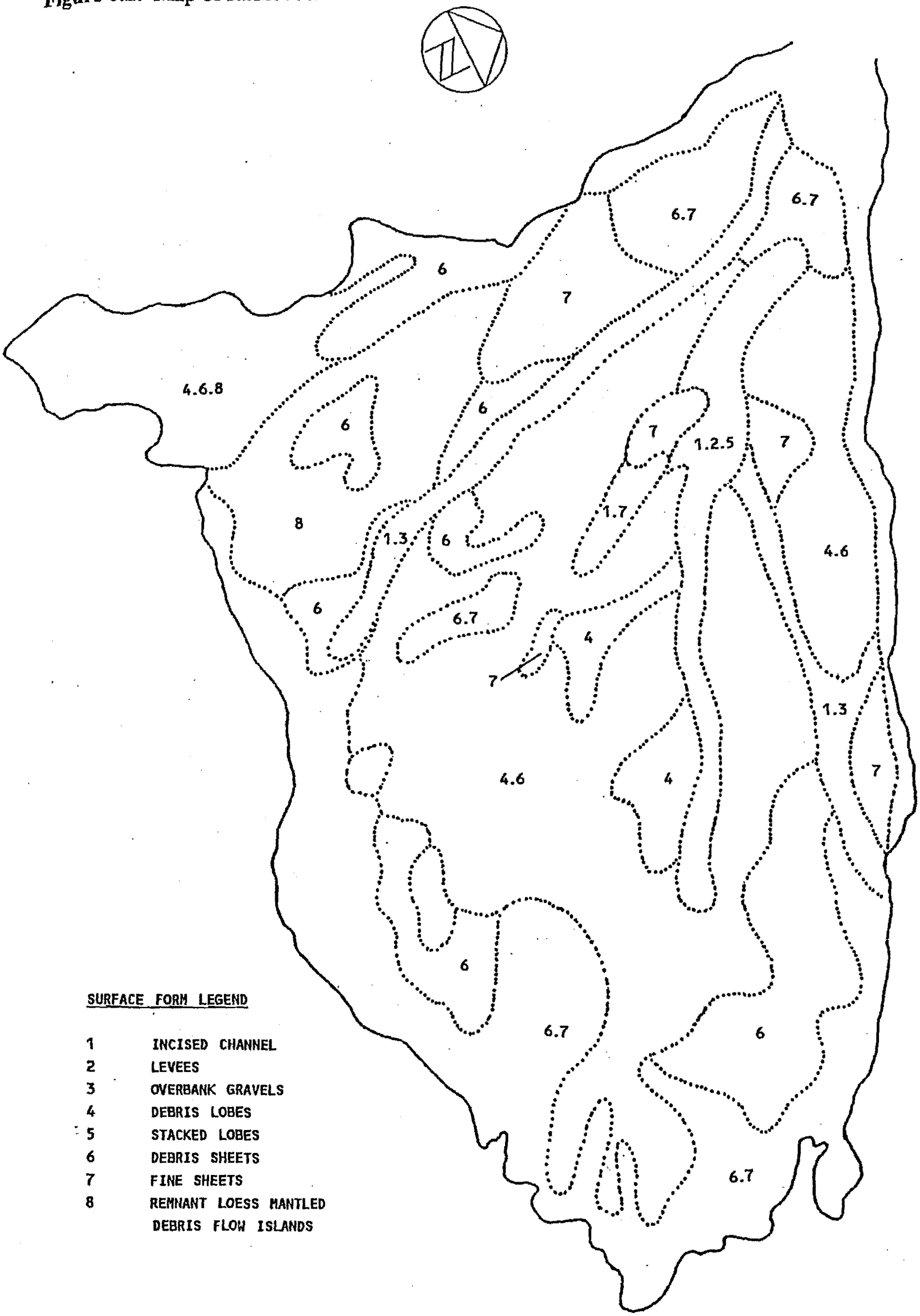
The map for surface form is presented in Figure 6.2. The legend was based on types of surface form described in chapter 2.4.2.

A radial pattern of surface form was evident. Debris flow lobes, levees and incised channels dominated the fan head and mid fan regions. Debris flow lobes and levees occurred alongside and down channels. Where channels had filled or blocked, debris flows breached the levees and formed extensive steep sided lobes down fan. The fan toe still contained debris flow lobes, but was dominantly composed of debris sheets and shallow channels. As a consequence microtopography was more subdued. Many of the features were subdued and difficult to recognise, reflecting a high degree of reworking by stream flow on the upper fan and the dilution of flows down the fan.

Narrow incised channels (abandoned and partially infilled channels as described in chapter 2.5.2, see Plate 6.1), extended from the fan apex to the mid fan and fan toe regions where debris lobes and sheets extended from the intersection points.

Plate 6.1. Old incised and partially infilled debris flow channel in the mid fan region.

Figure 6.2. Map of surface form.



6.2.3 Sedimentary form.

Sedimentological characteristics were described as part of the soil profile description. The legend is representative of the range of sedimentary classes encountered on the fan using observations of packing and texture (Eggleston, 1989), outlined in Table 6.1. Each sedimentary deposit was composed of one or more of the described sediment classes. The map for sedimentary form is presented in Figure 6.3.

The textural forms were used to group similar textural variations observed in the 1 metre deep profiles. Table 6.2. gives a description of the textural forms used.

Table 6.1. Description of sediment classes.

Sediment class	Packing class	Texture	Description
S1	P1	g	Open packed, clast supported, loose with no fine matrix.
S2	P2	gs gls gl	Open packed, clast supported, loose with an increasing proportion of fine matrix.
S3	P3	gs gzl gsl gls	Close packed, matrix supported, high proportion of fine matrix, loose to compact.
S4	P4	gs gzl gsl gls	Close packed, matrix supported, very compact, abundant fine matrix and very poorly sorted.
S5		s ls sl zl	Fine textured sands and loams.

Key:

g-gravelly

s-sands (s, ls)

l-loams (sl, l)

zl-silt loam

gs- dominant texture

Table 6.2. Description of textural forms encountered in this study.

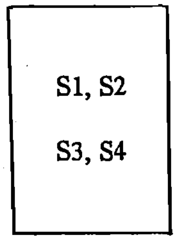
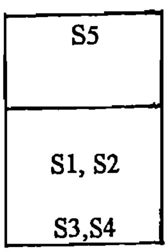
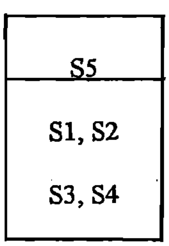
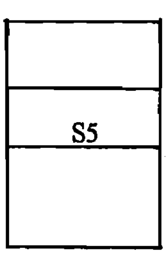
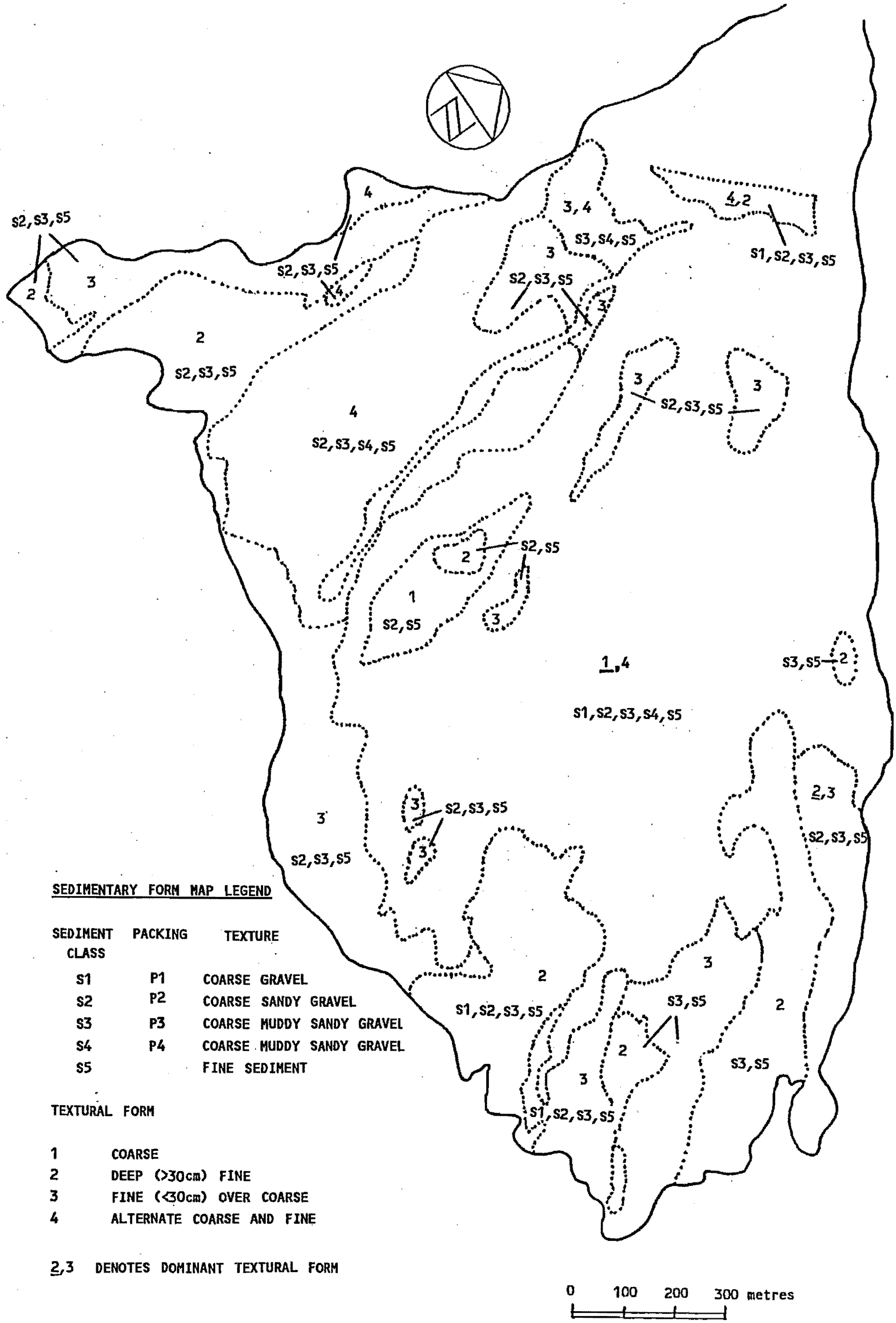
Texture profile	Textural form
	***Textural form 1*** Coarse textured profile, consisting of S1, S2, S3 and S4 alone or in combination.
	***Textural form 2*** Deep (>30 centimetres), fine textured sediments (S5), overlying coarse textured sediments (S1, S2, S3, S4).
	***Textural form 3*** Fine textured sediments (<30 centimetres), overlying coarse textured sediments.
	***Textural form 4*** Alternating fine and coarse textured sediments (S1, S2, S3, S4 and S5), in any combination.

Figure 6.3. Map of sedimentary form.



The fan was dominated by debris flow and sheet flood sediments with a small occurrence of stream flow sediments also present.

Debris flow sediments were identified by sediment class S4. They included mainly older debris flow sediments and were extremely poorly sorted, matrix supported and very compact (notably the older sediments, see Plate 6.2). The largest clasts measured 1 metre in diameter and were angular to subangular.

The more recent sediments commonly occupied sediment classes S3 and S2, being poorly sorted, matrix supported and less compact than S4 sediments. These were thought to have resulted from dilute debris flows and hyperconcentrated flows. The largest clasts measured 0.5 metres in diameter and were angular to subangular.

Stream flow sediments (S1), occurred in association with all other sediment classes, predominantly as thin lenses within sheet flood sediments, or superseding debris flow sediments (see Plate 6.3).

Fine sediments (S5) also occurred in association with all sediment classes usually at the surface and often as a thick layer resulting from low energy flow (see Plate 6.3). The older sediments comprised thick sections of S5 that were the due to the inclusion of loess.

Fan sediments were largely coarse, with textures ranging from coarse gravel to coarse sandy gravel to coarse muddy sandy gravel. Fine textures were silt loams, loams (sl, l) and sands (s, ls). Loamy sands and silt loams were the dominant textures.

Packing was dominated by P3 and P2, with P4 less common and P1 only rarely occurring. P1 was found in sequence above P3 sediments.

There was a slight change in packing down fan from P4 and P3 in the fan head and mid fan regions to P3 and P2 lower down the fan.

Sediments resulting from the more recent fan activity produced the majority of coarse textural profiles (textural form 1). Textural forms 4 and 2 were also common and were thought to represent areas low energy flow.

The fan toe was dominated by textual forms 2 and 3. This was interpreted as being a result of the washing out of fines from upper fan debris flow deposits, a greater occurrence of sheet flood deposits down fan, caused by low slopes and dilution of debris flows.

Plate 6.2. An example of the matrix supported, poorly sorted and compact sedimentary form typical of the older debris flow deposits.

Plate 6.3. A sequence of sedimentary forms found in the mid fan region.

The older surfaces on the left side of the fan were of either textural form 2 and 3, (due to the greater inclusion of reworked loess overlying reworked gravel), or textural form 4, where the loess mantle had been superseded by recent coarse sediments or interrupted during deposition by debris flow deposition (see Plate 6.4).

Plate 6.4. Compact layer of debris flow gravels through a predominantly loess profile.

6.2.4 Soil Stratigraphy

The maps for soil distribution and multisequal and unisequal soil distribution are included in this section (see Figures 6.4 and 6.5).

6.2.4.1 Soil profile forms.

Six simple soil profile forms were identified on the basis of the soil horizon development.

They were as follows:

Soil Profile Form	**Horizon Development Sequence**
1	A/C
2	A/BC/C
3	A/Bw/C
4	A/AB/Bg/Cg
5	O/Br/Cr
6	A/AB/Br/Bg/Bx

The identifying morphological properties for each profile form are presented in Tables 6.3, 6.4, 6.5, 6.6, 6.7 and 6.8.

Table 6.3. Soil profile form 1 (SPF1).

Soil Property[3]	**Soil Horizon**	
	A	C
Thickness (cm)	5-25	5->60
Moist colour		
hue	10YR> 2.5Y	2.5Y> 5Y
group	1>2	2>1
Mottling		
abundance	nil	nil
size		
Texture		
skeletal	m-v grv slt-m st	m-v grv m-v st
weathering	fr	fr
shape	a>sa	sa
fine	sl	ls>s
Structure		
grade	wk	sg
size	vf	
type	nt	
Packing class	nil	P3>P2
Texture profile form	gradational negative	
Structure profile form	subpedal	
Redox profile form	unoxidised	

[3] Refer Appendix A.

Table 6.4. Soil profile form 2 (SPF2).

Soil Property[3]	**Soil Horizon**		
	A	BC	C
Thickness	10-15	30	>40
Moist colour			
hue	2.5Y	2.5Y	2.5Y
group	1	2	5
Mottling			
abundance	nil	nil	nil
size			
Texture			
skeletal	m grv	m-v grv	v grv
	m st	m-v st	m-v st
weathering	fr	fr	fr
shape	sa	sa	sa>sr
fine	sl	ls	ls
Structure			
grade	wk	wk	sg
size	vf	vf	
type	nt	nt	
Packing class	nil	P3	P3
Texture profile form	gradational negative		
Structure profile form	subpedal		
Redox profile form	unoxidised		

[3] Refer Appendix A.

Table 6.5. Soil profile form 3 (SPF3).

Soil Property[3]	**Soil Horizon**		
	A	Bw	C
Thickness (cm)	15-20	20-35	>20
Moist colour			
hue	2.5Y	2.5Y	10YR >2.5Y
group	2	2	2>4
Mottling			
abundance	nil	fw	nil
size		f	
Texture			
skeletal	m grv m st	m-v grv m-v st	v grv m-v st
weathering	slt	slt	slt
shape	sa	sa>sr	sa>sr
fine	zl	sl>ls	ls>s
Structure			
grade	m>wk	m>wk	sg
size	vf-f	f	
type	nt	bl	
Packing class	nil	P2>P4	P2>P3
Texture profile form	gradational negative		
Structure profile form	epipedal		
Redox profile form	oxidised		

[3] Refer Appendix A.

Table 6.6. Soil profile form 4 (SPF4).

Soil Property[3]	Soil Horizon			
	Ah	AB	Bg	Cg
Thickness (cm)	15-20	5-20	35-50	>35
Moist colour				
hue	2.5Y> 10YR	2.5Y> 10YR	2.5Y> 5Y	5Y> 2.5Y
group	2>5	2>5	3>2	3>2
Mottling				
abundance	nil-fw	c-ma	ma	a
size	f	f-md	md	c
Texture				
skeletal	nil	nil	slt grv slt st	md grv slt st
weathering			slt-m	slt
shape			sa-sr	sa
fine	zl	zl	sl>zl	sl>ls
Structure				
grade	w-m	m	m	mass or sg
size	vf-f	f-md	md	
type	nt	bl	bl	
Packing	nil	nil	P3>P2	P3>P2
Texture profile form	gradational negative			
Structure profile form	epipedal			
Redox profile form	mottled			

[3] Refer Appendix A.

Table 6.7. Soil profile form 5 (SPF5).

Soil Property[3]	Soil Horizon		
	O	Br	Cr
Thickness	5-10	30	>35
Moist colour			
hue	10YR >2.5Y	5Y	5R
group	2>5	2	3
Mottling			
abundance	f	m	a
size	f	f	m
Texture			
skeletal	nil	slt grv	m-v grv m st
weathering		fr-slt	slt
shape		sa	sa>sr
fine	peat	sl	ls>sl
Structure			
grade	mass	w	sg
size		f	
type		bl	
Packing	nil	P3	P3
Texture profile form	gradational negative		
Structure profile form	subpedal		
Redox profile form	reduced		

[3] Refer Appendix A

Table 6.8. Soil profile form 6 (SPF6).

Soil Property[3]	Soil Horizon				
	Ag	ABg	Br	Bxg	Bx
Thickness (cm)	10	15	10	15-20	>80
Moist colour					
hue	10YR >2.5Y	10YR >2.5Y	2.5Y	5Y	10YR >2.5Y
group	2>1	2>1	3	3	4>3
Mottling					
abundance	f	ma	a	a	ma-a
size	f	f	m	c	c
Texture					
skeletal	nil	nil	nil	nil	nil
weathering					
shape					
fine	zl	zl	zl	zl	zl>cl
Structure					
grade	str	str	str	str	mass
size	vf	f	f	c	to c
type	nt	bl	bl	bl-prs	prs
Packing	nil	nil	nil	nil	nil
Texture profile form	uniform to gradational positive				
Structure profile form	bipedal				
Redox profile form	mottled				

[3] Refer Appendix A.

SPF1 dominated, occurring through the central and right hand fan regions. SPF4 and SPF6 were the next most common, occupying the fan toe and the left-hand side of the fan respectively. SPF5 occurred in patches along the fan toe and covered a similar fan area as SPF3, found in the right and central mid fan regions. SPF2 occurred in the central mid fan and were the least common.

6.2.4.2 Soil pattern.

Soil profile classes.

Soil profile classes were identified according to the following key morphological criteria:

1. Soil horizon sequence.
2. Presence of buried soil.
3. Skeletal and fine earth texture.
4. Redox profile form.

A description of each soil profile class is given in Table 6.9.

Soil mapping units.

Mapping units were based on the soil profile classes described in Table 6.9. Consociations (simple mapping units) and complexes (compound mapping units), were encountered. These are listed in Table 6.10. The map for soil pattern is presented in Figure 6.3.

Table 6.9. A description of the soil profile classes.

Parent material	Drainage	Soil profile class (SPC)	Features
Loess	Imperfect	6+	Deep silt or clay loams with dense fragipan. Strongly mottled and 2.5Y colours. Thickened aggrading A horizon.
Loess with interbedded debris flow gravels	Imperfect	6s	As above with compact debris flow gravel layers through out the soil. Mottled with 2.5Y colours.
Mixed loess and gravels	Very poor	5	Organic or peaty horizon over reduced subsoil horizons. Sandy loams with gravels.
Mixed loess and gravels	Imperfect	4	Silt loams over sandy loams with gravels throughout the soil
Mixed loess and gravels	Imperfect	4+	As above with thickened, aggrading A horizon.
Mixed loess and gravels	Poor	4w	Silt loams over sandy loams or loamy sands. Gravels throughout. Subsoil horizons mottled with reduced 2.5Y colours.
Debris flow gravels	Moderate	3	Silt loams over sandy loams and loamy sands. Stony profiles with 2.5Y and 10YR colours.
Debris flow gravels	Moderate	3+	As above with thickened, aggrading A horizon.

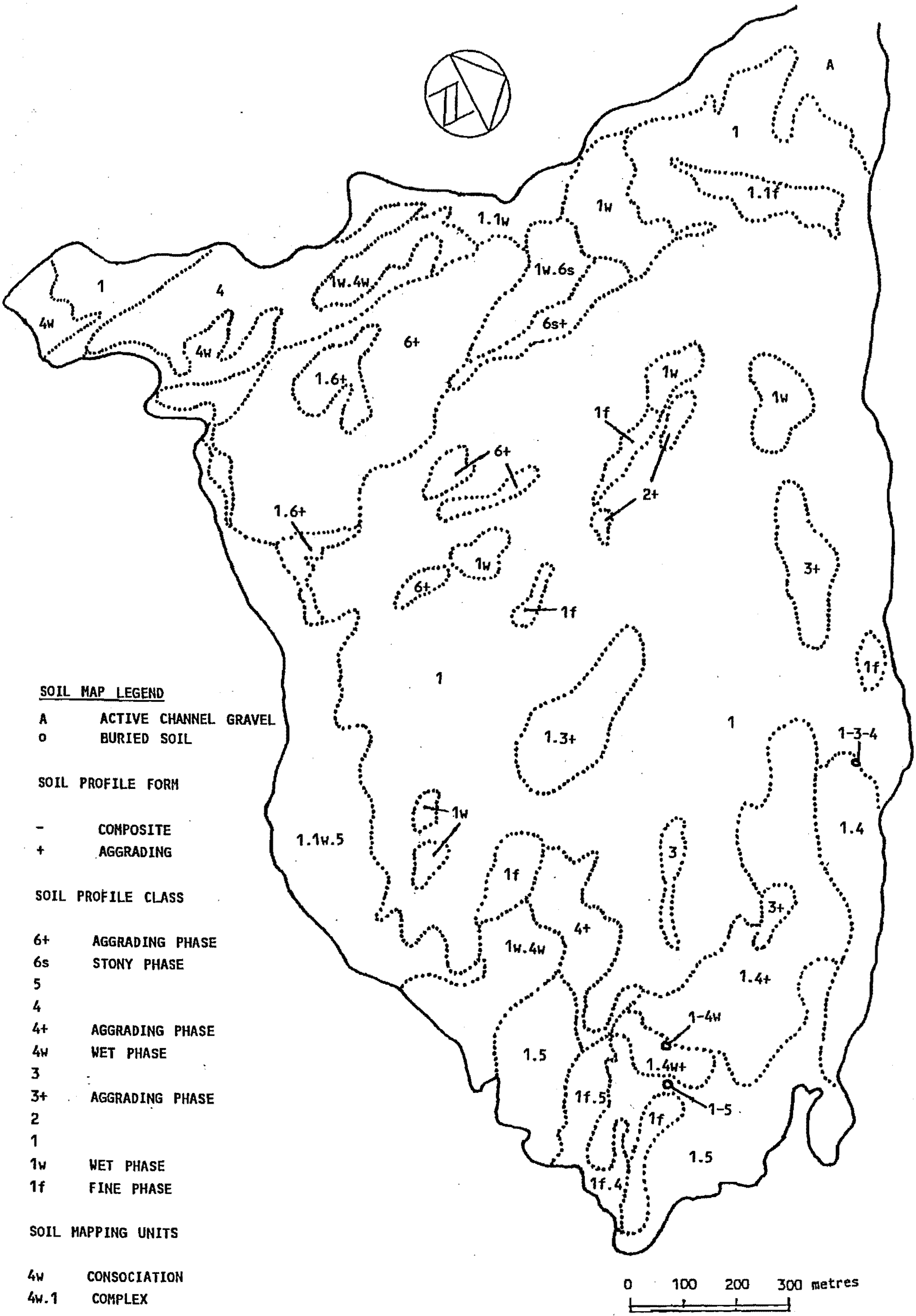
Debris flow gravels and fines	Well drained to poor	2+	Sandy loams over loamy sands. Stony profiles with BC horizon. Thickened aggrading A horizon.
Debris flow gravels and fines	Well drained to poor	1	Sandy loams over loamy sands and sands. Very stony profiles.
Debris flow gravels and fines	Poor to very poor	1w	Lenses of silt loams, loamy sands, sands, gravels and organic materials. 5GY to 10GY colours.
Debris flow fines	Moderate to imperfect	1f	Deep fine loamy sands ands, massive or single grained. 5Y colours dominant.

Table 6.10. Soil mapping units.

Soil mapping units	
Consociations	*Complexes*
6+, 6s+	1.6+, 1.6s+
5	1.5, 1f.5, 1.1w.5
4, 4+, 4w	1.4, 1.4w, 1.4w+, 1w.4w
3, 3+	1.3+
2+	
1, 1w, 1f	1.1f, 1.1w

SPF1 dominated, occurring through the central and right hand fan regions. SPF4 and SPF6 were the next most common, occupying the fan toe and the left-hand side of the fan respectively. SPF5 occurred in patches along the fan toe and covered a similar fan area as SPF3, found in the right and central mid fan regions. SPF2 occurred in the central mid fan and were the least common.

Figure 6.4. Map of the soil pattern.



6.2.4.3 Multisequal and unisequal soil pattern.

Using the concepts discussed in chapter 3.3.2.2 the soils were mapped in terms of whether soil profiles were aggrading, composite compound or simple.

The distribution map for multisequal and unisequal soils is presented in Figure 6.5.

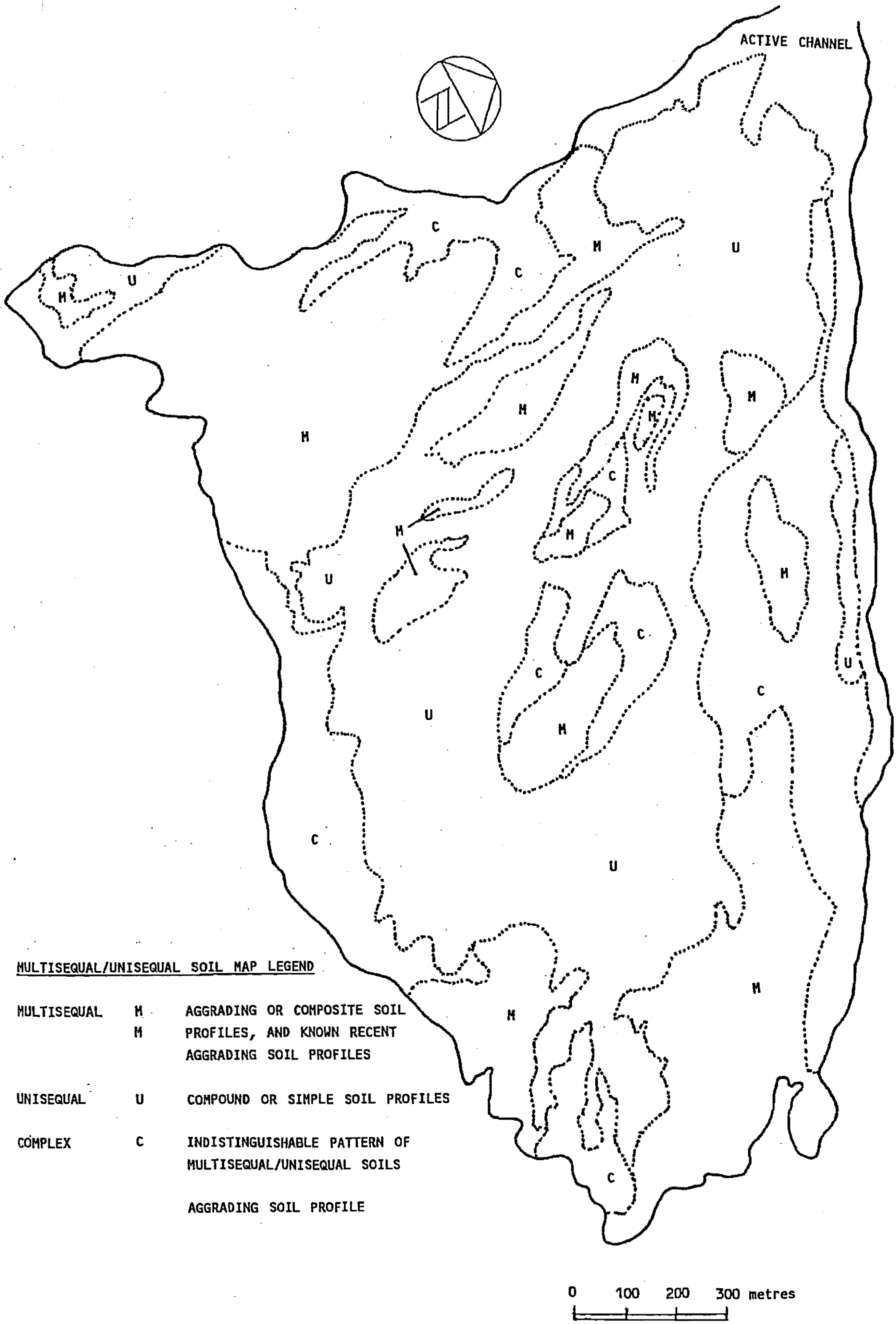
Multisqual soils were defined as being either aggrading or composite. They consisted of thin beds of sediment, variable in thickness. Where no soil development was evident these represented deposition within a single debris flow episode or deposition within closely timed episodes. The occurrence of multiple buried soils indicated stability between more sparsely timed episodes of deposition.

Unisequal soils incorporated thicker, more uniform deposits in which compound or simple soil profiles were formed. They were also shown to be associated with the more recent coarse textured soils derived from debris flow deposits. They occupied the fan head and central mid fan regions.

The multisequal soils were found in patches throughout the mid fan and in the fan toe regions. They were associated with the finer textured recent soils originating from sheet flood deposition. Multisequal soils also existed where thin layers of recent sediments had been deposited over older loess and gravel derived soils. Thin deposits formed aggrading soil profiles while thicker deposits formed composite soil profiles.

There were a number of regions where the pattern was too complex to delineate, especially where thick, overlapping debris flow lobes extended into sheet flood sediments.

Figure 6.5. Map of multisequal and unisequal soil distribution.



6.2.5 Geomorphic surfaces.

This study has used simple soil profile forms as a means of identifying geomorphic surfaces and buried geomorphic surfaces (discussed in chapter 3.3.1.1). The map for geomorphic surface distribution is presented in Figure 6.6.

Aggrading geomorphic surfaces and buried geomorphic surfaces were recognised within a vertical profile using similar concepts as outlined by Bos and Sevink (1975).

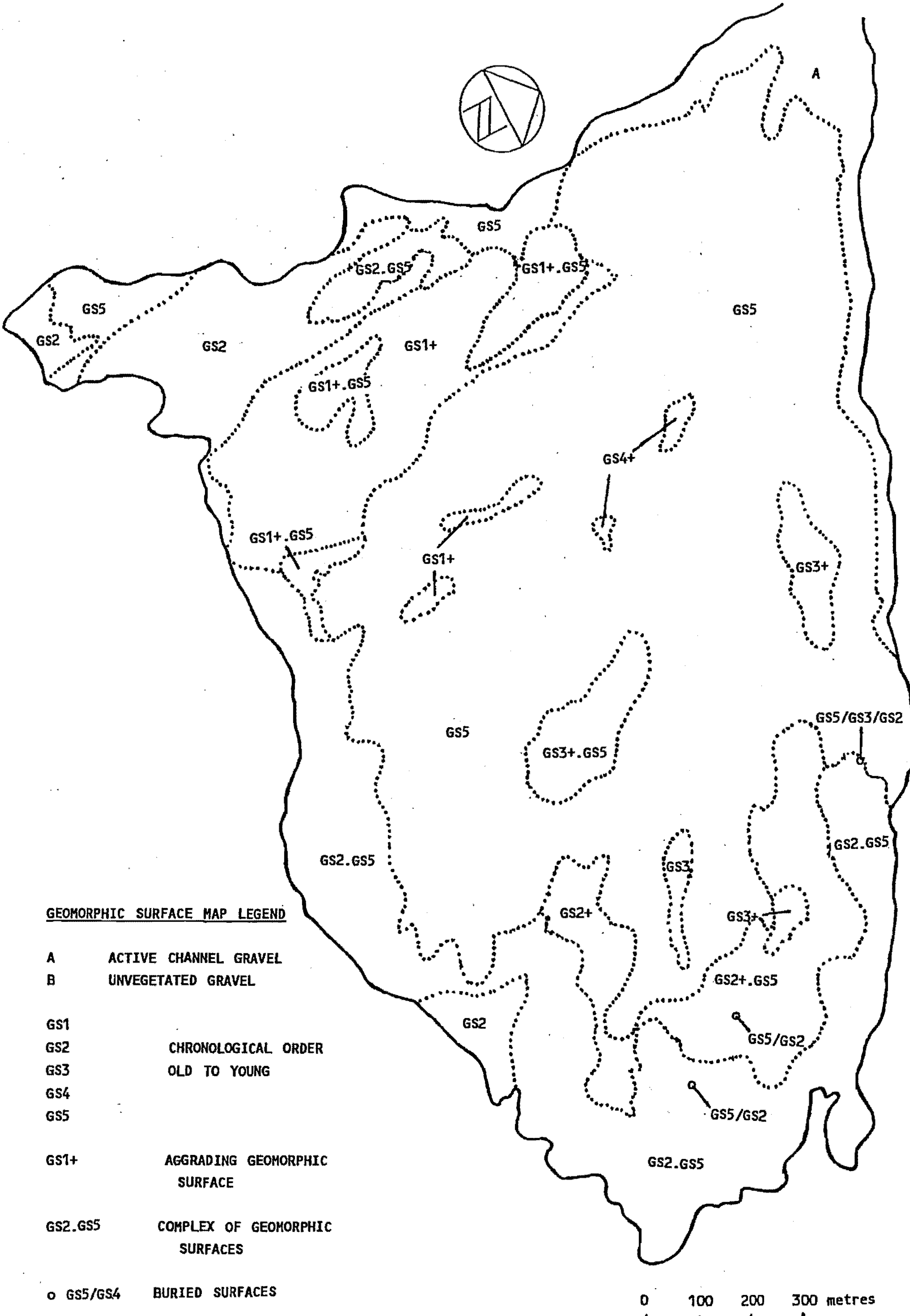
The uppermost boundary of the soil or buried soil was used to identify the geomorphic surface or buried geomorphic surface.

There were five geomorphic surfaces identified in this study. Their relationship with the simple soil profile forms on which they lay was as follows:

Geomorphic Surface (GS)	**Associated Simple Soil Profile Form**
GS5	A/C
GS4	A/BC/C
GS3	A/Bw/C
GS2	A/AB/Bg/Cr or O/Br/Cr
GS1	A/ABg/Br/Bxg/Bx

GS5 was the youngest and most extensive surface, occupying the central and right hand fan regions and representing phases of deposition from the 1920's up until the late 1970's. GS3 persisted as small remnant islands within GS1. The aggradational surface, GS2 was formed on reworked gravels and loess and extended mainly along the fan toe. GS1 was an aggradational surface of the Late Pleistocene, veneered by 2.5 metres of loess. It was exposed as a single island on the left side of the fan and surrounded by the younger surfaces.

Figure 6.6. Map of geomorphic surface distribution.



6.3 Laboratory results.

6.3.1 Soil chemical analyses.

The results from the following chemical analyses are graphically represented in Figures 6.7 to 6.13 inclusive.

6.3.1.1 Soil pH.

pH (H_2O).

Values for pH tended to decrease with increased soil age and decreased drainage. The older profiles showed uniform or decreasing pH with depth, whereas pH in the two youngest soils increased down the profile. The profiles situated in the fan toe were at best moderately acidic and in the case of sampled profile RT2, extremely acidic in the subsoil.

Δ pH.

Δ pH = pH($CaCl_2$) - pH(H_2O). The values for sampled profiles are given below.

Sample	LM1	LT2	RT2	RT1	CM3	CM4
1	-0.7	-0.6	**-0.3**	-0.5	-1.6	-0.7
2	-0.8	-0.5	-1.1	-1.1	-1.1	-0.9
3	-1.0	-0.6	-1.2	-1.3	-1.3	-1.1
4	-1.2	-0.7	-0.8	**-1.6**	**-1.4**	-0.7
5	-1.2	-0.9	-0.6	-1.3	-1.2	-0.2
6	-1.0	-1.1	-0.6	**-1.4**	-1.2	-0.4
7	**-1.4**	-1.3	-0.7	-0.7	-1.0	-0.4
8	-1.1	-1.3			-0.7	-0.6
9	**-1.9**				-0.4	
10	-1.0					
11	-1.0					
12	-0.7					

All values for Δ pH were negative. Profile LM1 showed a relatively uniform trend with depth, LT1, RT2 and increased with depth and CM3 and CM4 decreased with depth. The values highlighted are near or greater than 1.5. Horizons carrying such a high positive charge are unlikely to allow nitrate adsorption (Black and Waring, 1979).

6.3.1.2 Organic carbon.

All profiles had low topsoil organic carbon values decreasing rapidly to very low in the subsoil, with the exception of RT2, in which the topsoil was medium. Values for the younger profiles (CM3 and CM4), were comparable with those of the older profiles, indicating rapid organic matter accumulation. Values for profile CM4 varied down the the profile, an indication of the organic matter included within these recent deposits and indistinguishable buried soils.

Profiles RT2 and LT1 were situated in the lower fan toe resulting in a greater accumulation of organic matter as indicated by higher organic carbon values. The exceptionally high value in profile RT2 represents a buried peaty horizon.

6.3.1.3 Phosphorus (H_2SO_4 extractable).

Overall topsoil values were high to very high and subsoil values ranged from low and very low in the B horizons of profiles (these were most noticeable in the profiles containing loess) to high in the remainder of the subsoil. The low values in the B horizons of profiles were assumed to be a result of greater weathering and leaching. There was a slight increasing trend in phosphorus values from old to young profiles, however this was really only evident in the profiles derived from debris flow sediments (RT1,CM3 and CM4).

6.3.1.4 Oxalate extractable aluminium and iron.

Oxalate aluminium (Al_o).

All profiles showed very low Al_o values, constant or decreasing with depth. The highest values were found in profile RT2 where transformation is associated with the strongly acidic conditions. The lowest values were associated with the profile, CM4. This was a reflection of the minimal soil development.

Oxalate iron (Fe_o).

The values for Fe_o were higher than for oxalate aluminium. All profiles had generally low values. The lowest values were more common in the younger profiles and where reduced soil conditions persisted.

6.3.1.5 Cation exchange properties.

Total exchangeable bases (TEB).

E B

Generally all profiles displayed low to very low Total exchangeable base values. There was only a small decrease from older profile to younger profiles. Medium values were common in the topsoils of the profiles occupying the fan toe. This may have been a due to the accumulation of organic matter. Subsoil values are lowest in these profiles, a result of leaching. The effects of leaching are best represented in the older profiles derived from loess, where cations (mainly Ca and Mg), increase with depth in the subsoil. Calcium cations are the greatest contributor to the bases, followed by magnesium, predominantly in the loess derived soils of profiles LM1 and LT1.

KCl extractable aluminium and hydrogen, KCl(Al+H).

Low values were found in the topsoils of all profiles and throughout the two youngest profiles CM3 and CM4. These two profiles were moderately drained due to their high sand content. High values were found in the more developed profiles, in the Br horizon (LM1, LT1 and RT2), and in the Bw horizon of profile RT1. All four profiles were subject to imperfect to poor drainage conditions. In most cases increased values coincided with a decrease in pH.

Cation exchange capacity (CEC) and effective cation exchange capacity (ECEC).

The majority of these values were in the range of low to very low with the exception of profile RT2 which had medium CEC values in horizons of high organic carbon content. Higher values for both CEC and ECEC showed a good association with increased levels of organic carbon. Slightly higher values in the soils containing loess (LM1, LT1 and RT2), compared to those profiles derived from debris flow sediments (RT1, CM3 and CM4), suggested an influence on CEC due to differences in particle size. Differences between CEC and ECEC were most evident in the profiles occupying the fan toe (RT2, LT1 and RT1), where pH values were low.

Percent base saturation (%BS).

Generally profiles showed very high %BS values in the topsoil, an initial decrease in the subsoil followed by an increase at depth. Values for the younger profiles were very high throughout the entire profile, whereas in the older profiles medium values were common to the subsoil. Very high values lower in profile LM1 may be attributed to increased calcium cations. Profile RT2 displayed very low values in the subsoil, corresponding with strongly acidic conditions in the lower profile.

Figure 6.7. Plots of pH (H_2O) with soil depth.

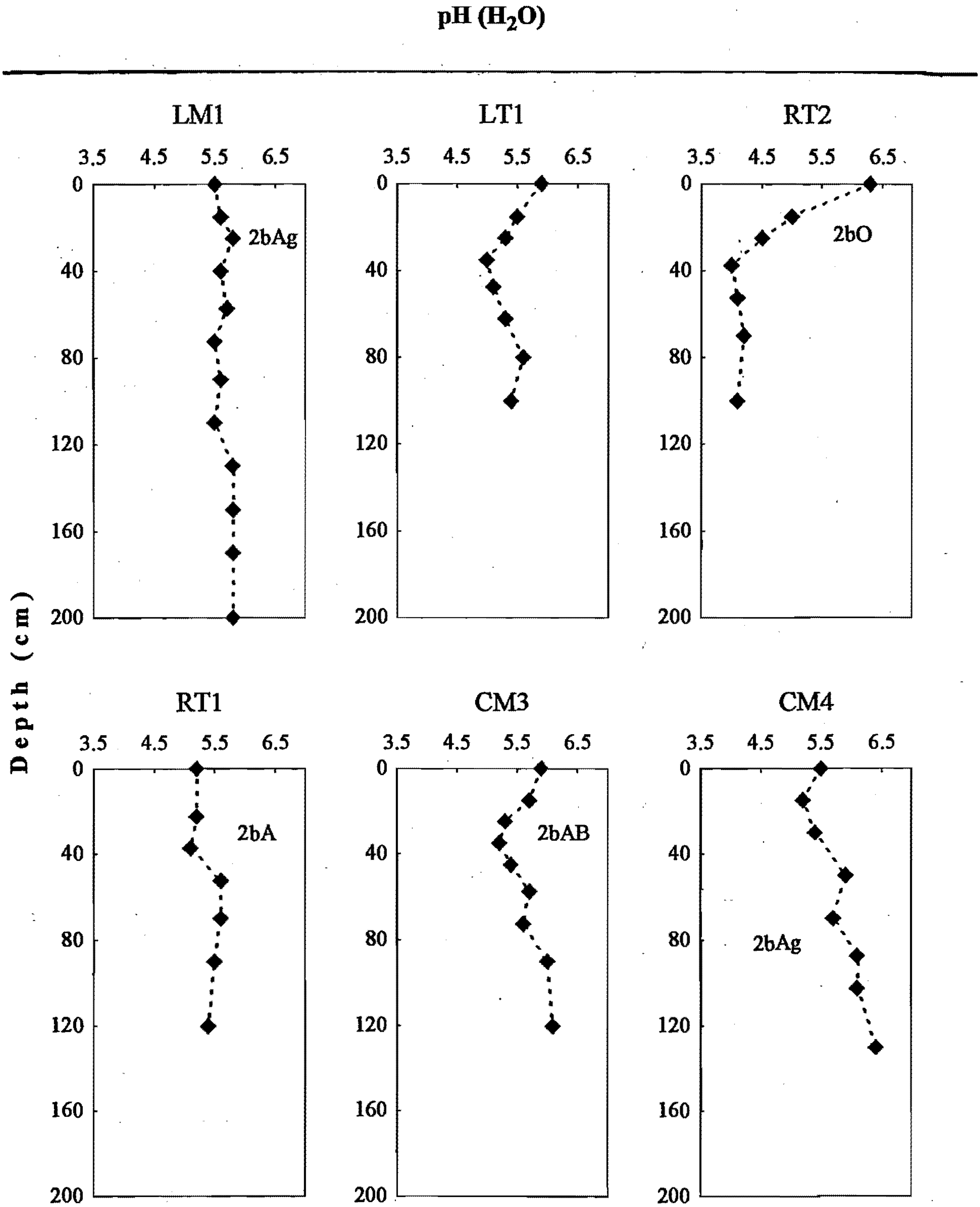


Figure 6.8. Plots of organic carbon with soil depth.

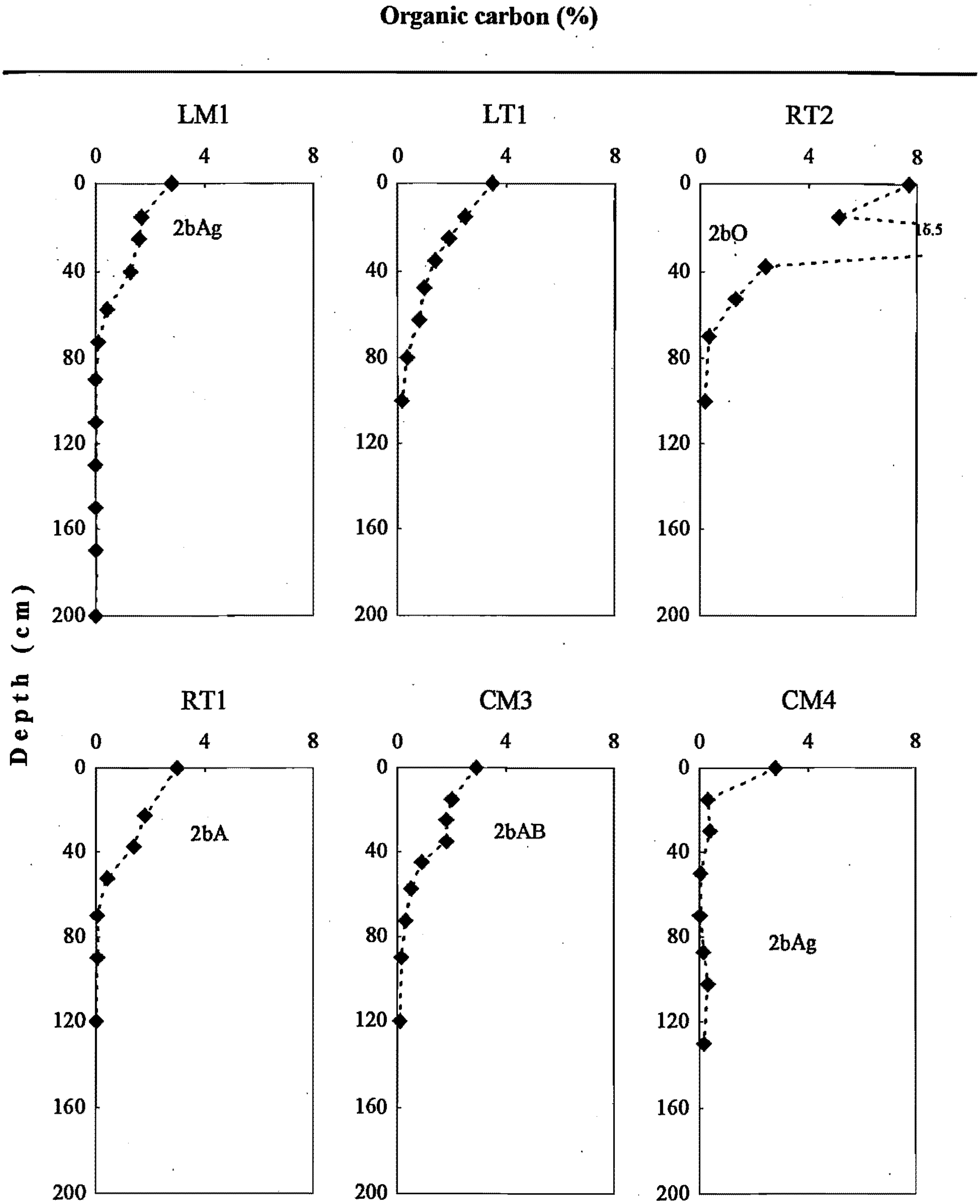


Figure 6.9. Plots of H_2SO_4 extractable phosphorus with soil depth.

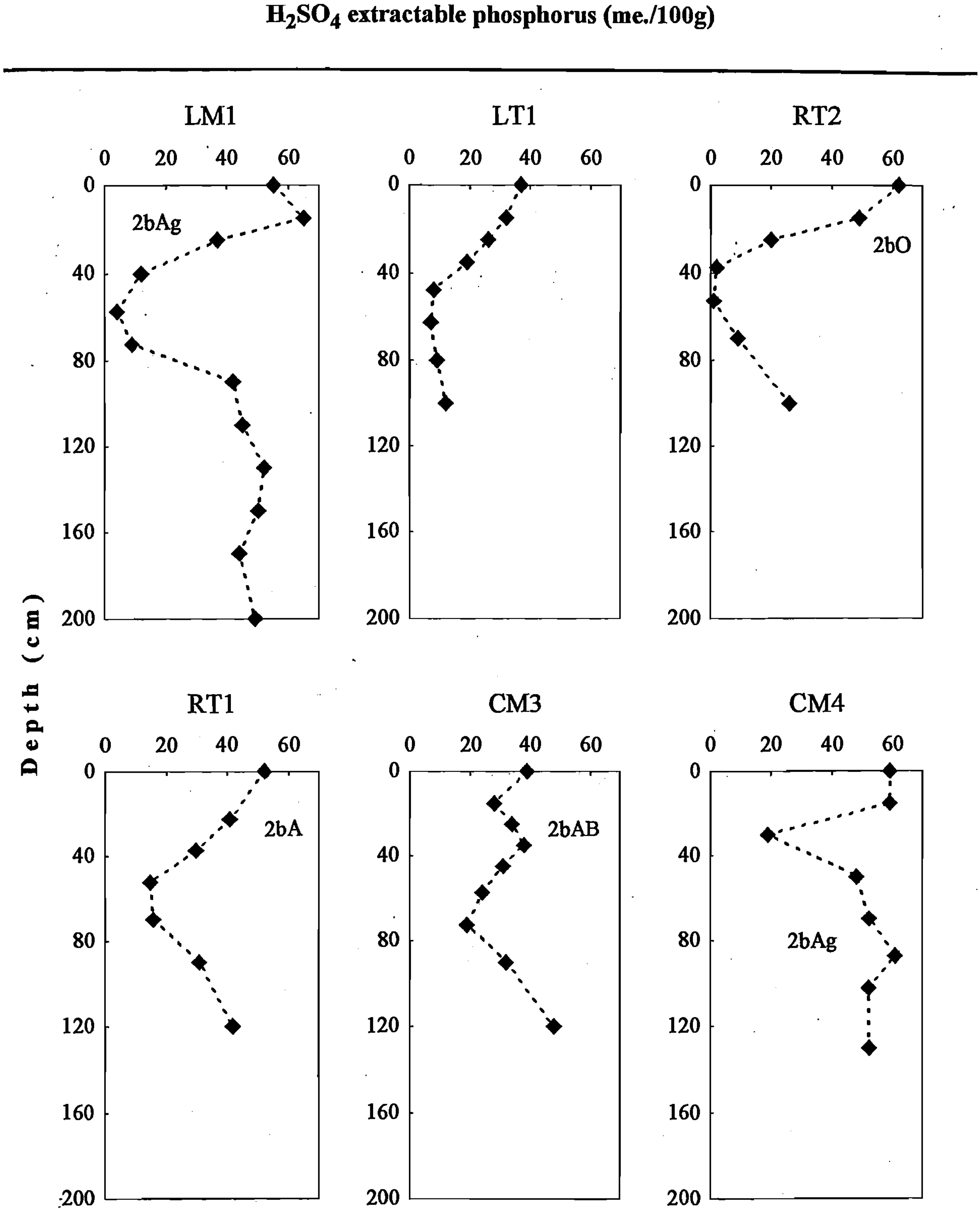


Figure 6.10. Plots of Oxalate extractable aluminium and iron with soil depth.

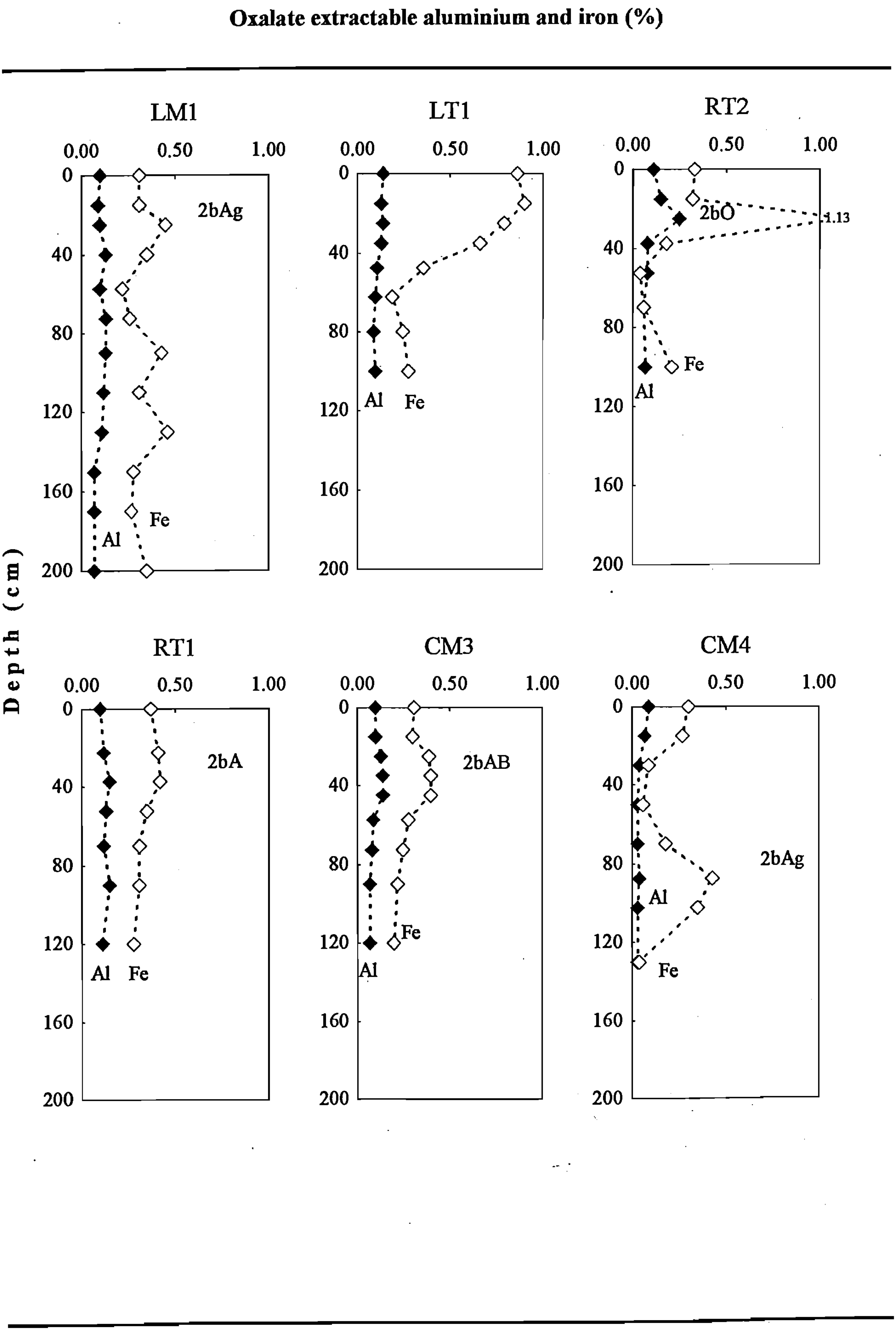


Figure 6.11. Plots of total exchangable bases with soil depth.

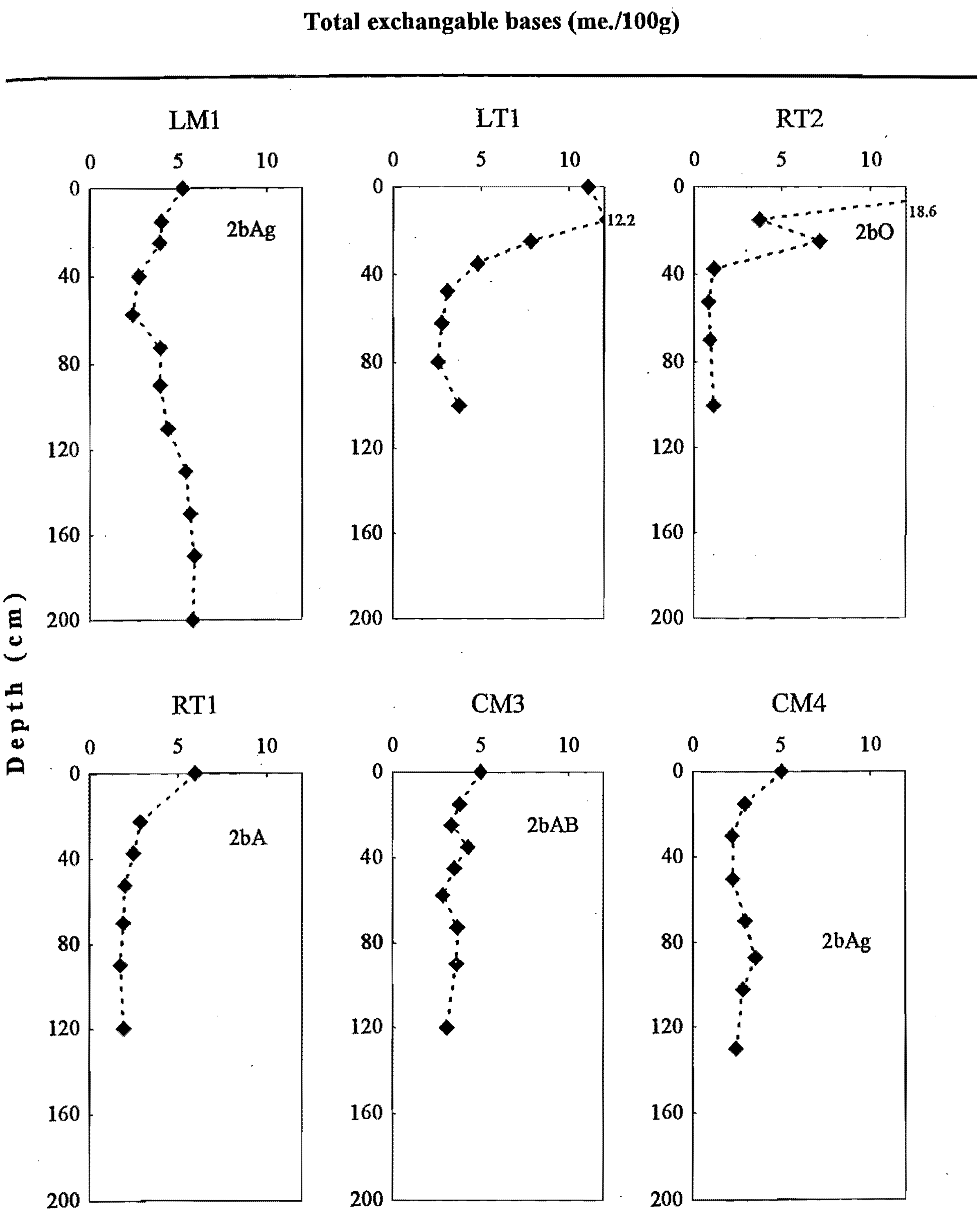


Figure 6.12. Plots of KCl extractable aluminium and hydrogen with soil depth.

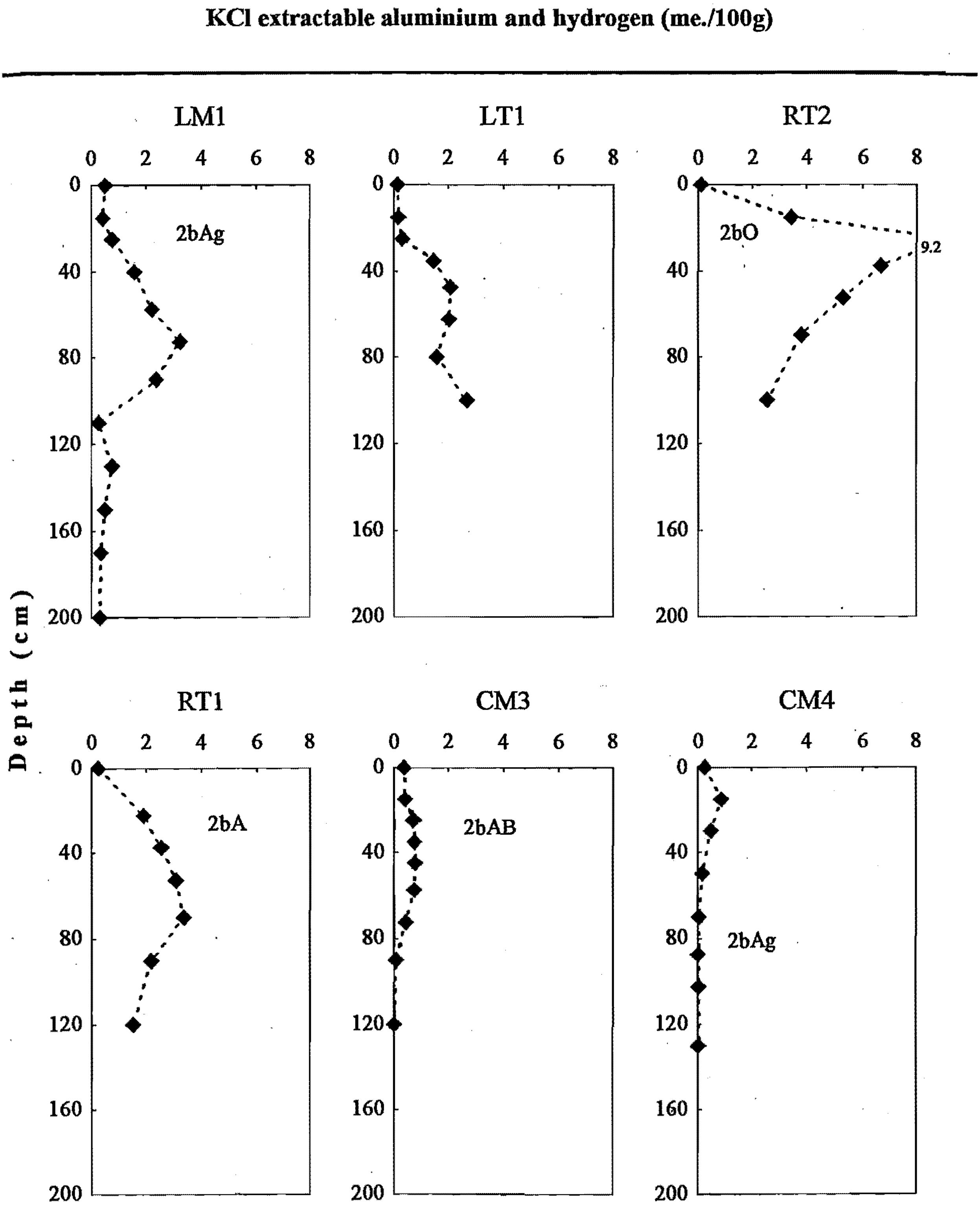
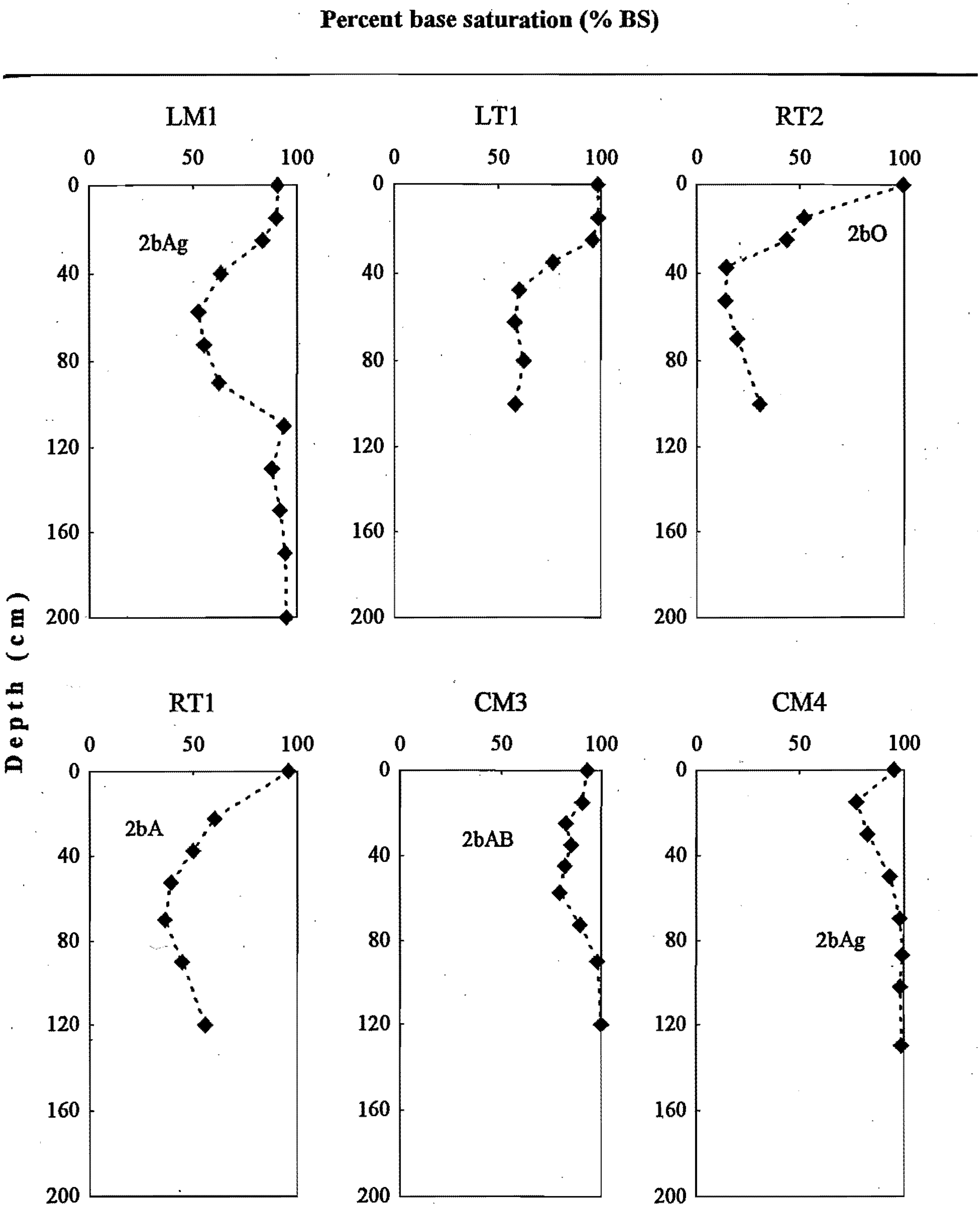


Figure 6 13. Plots of percent base saturation with soil depth.



CHAPTER 7
INTERPRETATION AND DISCUSSION

CHAPTER 7.0 INTERPRETATION AND DISCUSSION.

7.1 Process-form relationship.

7.1.1 Fan morphology.

7.1.1.1 Gross morphology.

Gross morphology is a reflection of drainage basin size, fluid momentum and the supply zone width at the fan head. These factors influence the size, shape and slope of the fan.

Bull (1977) stated that fan size and drainage basin size should be approximately the same, debris flow fans were steeper, smaller and more elongate than alluvial fans.

Fan size.

The Bullock creek fan covered an area nearly 2.8 times greater than its drainage basins. Reasons for this apparent discrepency were:

1. The drainage basins were deeply incised providing a greater volume of sediment than was depicted by the measured drainage basin area.
2. The eastern drainage basin previously active was inactive and had not contributed to recent debris flow activity. This had provided a large volume of sediment to the fan in the past.
3. The region through which the transport zone of the fan system passed had been incised providing more sediment for deposition on the fan.

Fan shape.

The fan subtended an angle of 85 degrees. This was in accordance with the 90 degree angle suggested by Rachocki (1981) for debris flow dominated fans.

Fan elongation was evident on the right hand side. Recent debris flow activity had been more dominant here, reflecting a greater fluid momentum associated with debris flow deposition.

Fan slope.

Debris flow activity does not generally occur on slopes less than 5 degrees (Costa, 1984), unless sediments have a high clay content or flows are confined at the fan head. The overall slope of the Bullock Creek fan was less than 5 degrees suggesting domination of alluvial deposition. It is suggested that debris flows moved to encompass the greatest change in relief present on the fan (right side of the fan). Here the slope must have been sufficient for debris flow. Two other factors were considered to contribute. The upper two zones of the fan system had greater slopes (ranging from 10 to 20 degrees). This may have provided the debris flows with sufficient momentum to move on the lesser fan slopes. Dilution of flows may have allowed the movement of debris flows on lower slopes.

7.1.1.2 Surface morphology.

The surface morphology of the fan comprised steep fronted terminal lobes, marginal levees (depositional surface forms), deeply incised U-shaped channels (erosional surface form), all associated with debris flows. Large surface boulders and stones were also a feature of the depositional surface forms.

More subdued surface forms included stacked lobes, hummocky topography (as described by Eggleston, 1989) and sheet surface forms. It proved difficult to determine the depositional processes associated with each of these forms. This was because of the high level of fluvial reworking following deposition and the inherent variability within the hyperconcentrated flow continuum and the similarities with stream flow surface forms (Costa, 1988; Wells and Harvey, 1987). Tillage and other agricultural practices greatly reduced the definition of surface forms also.

It was thought that the stacked lobes described by Wells and Harvey (1987), as transitional flow deposits, had originated from dilute debris flows and that hyperconcentrated flows were responsible for the majority of sheet surface forms rather than the down fan coalescing of debris flows. The hummocky topography was attributed to the reworking of surface forms by stream flow processes as suggested by Eggleston (1989).

Reworking of surface forms was an important feature on this fan. Older debris flow channels had been reworked in a similar manner to those described in chapter 2.5.2. However, it was thought that the majority of reworking occurred within the same storm event as the debris flow activity rather than between storm events.

7.1.2 Sedimentary form.

7.1.2.1 Fan sediments.

The majority of fan sediments were poorly sorted, and massive, consisting of clasts supported in a thin sandy matrix. These were included in the sediment classes S4 and S3.

Other sediments encountered on the fan formed a second group (similar to the group containing intermediate and water-laid sediments described by Bull, 1972). They were usually poorly sorted, massive or laminated, commonly unimodal, and dominantly clast supported in coarser sediments. Sediment classes S2, S1 and S5 were used to identify this group of sediments.

It was hoped that a distinction could be made between sediments derived from stream flow and those derived from hyperconcentrated flow. This was not possible due to the apparent high proportion of fluvial reworking of original deposits during debris flow events. It was assumed however that because the majority of sediments were massive that hyperconcentrated flow dominated over stream flow during initial deposition.

7.1.2.2 Bedding.

Bedding sequences were used to identify changes in the hydrolic conditions at the time of deposition. The packing criteria given in chapter 6.1.2 were used to identify these changes.

Debris flow deposits were recognised as thick beds of poorly sorted, matrix supported clastic sediments often up to 2 metres thick. Often these displayed abruted bedding contacts with underlying sediments as observed by Eggleston (1989). Bed thickness decreased slightly down fan as the flow discarded the coarsest fragments to maintain movement on the lower slopes. Lateral variation was evident in debris flow lobes where bed thickness decreased towards the margins of the deposit. Inverse grading was not predominant within individual beds.

Sheet flood sediments comprised numerous beds, highly variable in thickness and shape, similar to the bedding in the sheet flood deposits described by Bluck (1967). Bed thickness was greater in the fan head and mid fan regions than in the fan toe. This suggested that a greater proportion of the sheet flood sediments observed in the upper fan regions were derived from hyperconcentrated flows, whereas in the fan toe a decreased sediment to water ratio and increased fluvial reworking produced thinner beds more variable in texture and size.

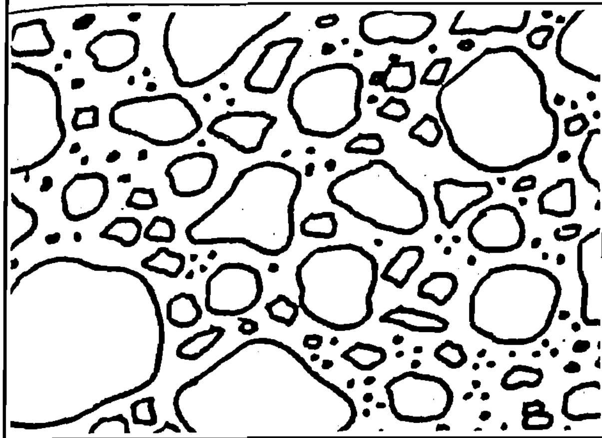
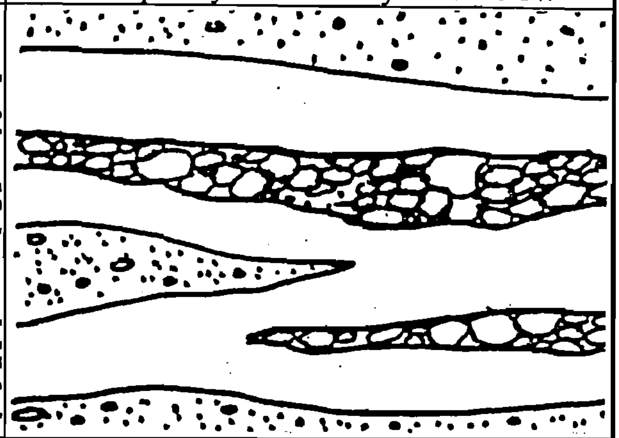
Several bedding sequences were observed. Commonly finer sheetflow sediments superseded or separated debris flow deposits. This occurrence may have been similar to the sequence described by Bluck (1967), where fluvial deposits were found to supercede debris flow deposits. The alternation of debris flow surges and slurry flows during debris flow activity (Pierson, 1980b), supports the occurrence of this bedding sequence. However it was not possible to conclusively relate adjoining sediment beds to the same depositional event. This was because several events were known to have occured within years of each other and the deposition of by debris flows varied laterally over this time (Pierson, 1980b).

7.1.3 Process and form related.

By combining surface and sedimentary form observations and knowledge of the dominant sediment transport processes in the fan system, process could be related to form as stated by Denny (1967).

Two main types of fan sediment were recognised and grouped as either coarse debris flow sediments or fine sheet flood sediments (see Figure 7.1). The use of surface form was useful in differentiation of debris flow deposits. The separation of hyperconcentrated flow and stream flow was not possible, as was found by Bull (1972) and Wasson (1977) who used only sedimentary criteria. ?

Figure 7.1. Description of the two main sediment groups encountered on the fan.

Coarse debris flow sediments	**Fine sheet flood sediments**
Viscous, clastic debris flows	Hyperconcentrated flows and flows subsequently reworked by stream flow
	
Massive and bimodal	Laminated or massive and commonly unimodal
Matrix supported	Clast supported in coarser sediments

7.2 The soil pattern.

7.2.1 Debris mantle, debris mantle regolith and the soil pattern.

The character and distribution of the debris mantle is primarly controlled by the mode of deposition, and the intrinsic nature of the fan system.

On the Bullock Creek fan the debris mantle regolith was related to the occurrence of debris flow deposition, hyperconcentrated flow, stream flow deposition, fluvial reworking and loess accumulation. Distribution was similar to the radial pattern described by Eggleston (1989) and that given by Tonkin and Eggleston (1991) for debris flow dominated fans.

There was generally no reduction in texture down fan due to the homogenous nature of debris flow deposits and the erosion and transport of fan head sediments to the lower fan region.

Notable differences between the model and this study were the inclusion of loess (thought to have accumulated during a period of minimal fan activity), fluvial reworking of fan sediments, including the washing of fines from debris flow deposits. These factors provided for a complex distribution pattern.

Incised channels were a common feature of the fan head and mid fan regions. A resulting feature was the down fan deposition of intermixed source area sediments and eroded fan sediments.

Textural variations, the inclusion of pre-weathered sediments and the depth of the debris mantle were all important factors affecting the soil pattern.

Textural variations were related to deposition type and reworking of sediments. Finer sediments allowed for more rapid weathering and where deposits were thin revitalised the soil nutrient status. The reworking of and subsequent down fan deposition was evident in both old and recent soil profiles. Debris mantle regolith consisting of pre-weathered loess and gravels such as for soil profile form 2 (SPF2) were found to interfinger the soils formed in loess in the fan toe region. As a consequence these soils may have appeared more developed than they were.

The left side of the fan and the fan toe consisted mainly of multisequal soils (refer Figure 6.5); sheet flood deposits consisted of thin multiple layers of debris mantle and where stability was sufficiently long, multiple layers of debris mantle regolith. The important features distinguishing multisequal soils from their unisequal counterparts are discussed in chapter 7.2.6.

7.2.2 Stratigraphy.

Five geomorphic surfaces were identified on the fan using the soil horizon sequence shown in chapter 6.2.4. Their relative stratigraphy was used to reconstruct the erosional and depositional history of the fan.

The oldest ~~surface~~ geomorphic surface 1 (GS1), formed in the Late Pleistocene was an aggradational surface and was subsequntly veneered by up to 2.5 metres of loess. The accumulation of loess suggested that the fan was stable during this period. Charcoal situated near the loess surface (interpreted as being the cessation point of loess deposition) was dated (refer Appendix A for detailed analysis) at 3680 ± 60 years B.P.. It is suggested that in this period loess deposition decreased relative to deposition from the drainage basins (i.e. drainage basin sediment supply increased, resulting in deposition on the fan).

Geomorphic surface 2 (GS2) was formed in the mid to early Holocene on gravels and loess eroded from the upper fan region.

The remaining geomorphic surfaces were formed predominantly on deposits resulting from fan activity during the late Holocene. These surfaces displayed an echelon overlap of successively younger geomorphic surfaces. Geomorphic surface 5 (GS5) was the youngest of these and covered over 60 percent of the fan surface. Only small areas of geomorphic surfaces 3 and 4 were left exposed (refer Figure 6.6. in chapter 6.2.4). The predominance of younger geomorphic surfaces on the fan suggested increased debris flow activity in recent times. This agreed with the high occurrence of activity over the past 100 years as documented by Pierson (1980b).

7.2.3 Periodicity.

Within the youngest soils, buried surfaces were difficult to distinguish, suggesting that periods of stability had been very short resulting in a large proportion of aggrading and composite soil profile forms. The model outlined in chapter 3.3.2.2 (Figure 3.7) was used to encompass the soil profile forms found.

The oldest soil profile possessed a thickened A horizon (see Plate 7.1). This represented the addition of sediment layers over time, sufficiently thin to prevent the formation of a separate soil horizon sequum.

The low number of older sufaces and associated soils suggested periods of stability (K cycles) were longer during the late Pleistocene and early to mid Holocene. This was further reinforçed by the accumulation of loess, at a time when fan activity was minimal. However, it is probable these soils (predominantly those with the horizon sequence A.Bw.C) have developed toward a common persistent soil profile form (Yaalon, 1971; Tonkin and Basher, 1991), thus simplifying the apparent stratigraphy.

Plate 7.1. Aggrading soil profile with thickened A horizon.

7.2.4 Development sequence.

Both temporal and spatial controls were a feature of soil distribution. The presence of five geomorphic surfaces indicated a temporal domination of the soil pattern, with the two oldest soils formed from sediments containing loess displaying a greater degree of spatial variability.

The soils relating to GS2 displayed the greatest spatial variation. They occupied the lower-mid and fan toe regions where drainage ranged from imperfect to very poor.

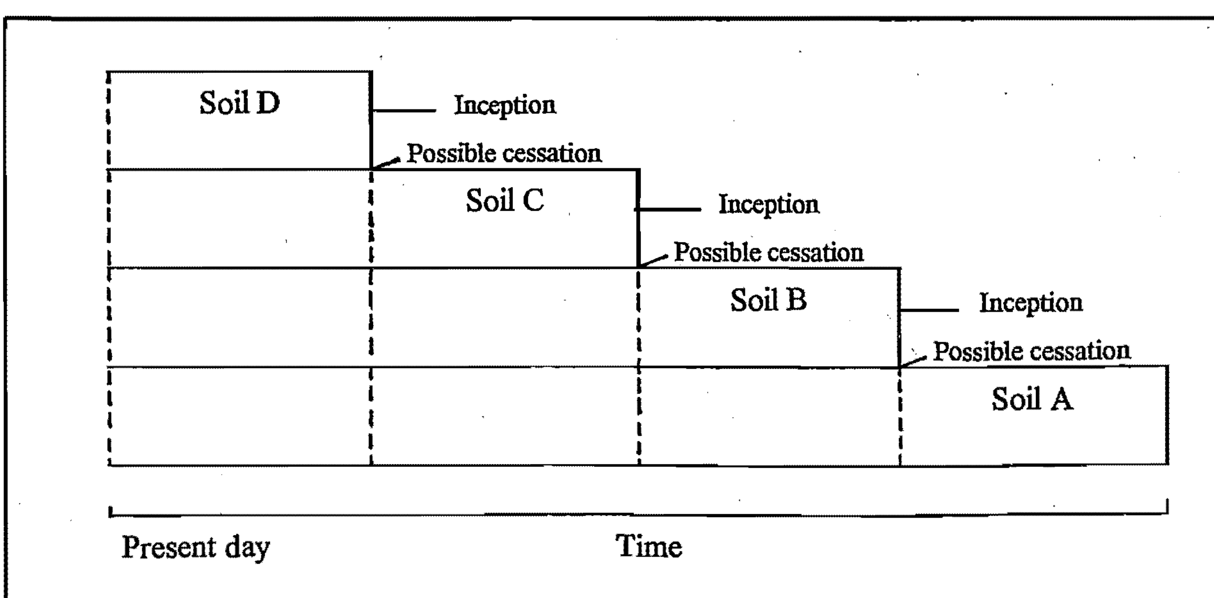
The horizon sequences representing the different stages of soil development found on the fan are presented in Table 7.1.

Table 7.1. Soil development sequence on Bullock Creek fan.

		Soil catena		
	1	A/C		
Stage of soil	2	A/BC/C		
development	3	A/Bw/C		
	4	A/AB/Bg/Cg	A/ABg/Br/Cr	O/Br/Cr
	5	Ag/ABg/Br/Bxg/Bx		

The sequence of soils represented a post-incisive, non strict chronosequence with a time transgressive imposition. Figure 7.2 represents the relationships between soil incepetion, soil cessation and duration of soil development encountered in this study and the resulting soil chronosequence model.

Figure 7.2. A model representing the soil chronosequence observed.



Inception ranged from the Late Pleistocene to the late Holocene. Not all of the soils had passed though the same point of development for the following reasons. The soils were formed from differing debris mantle, originating from source zone sediments, fan sediments and external additions (e.g. loess). This has effected the physical, chemical and mineralogical properties of the initial regolith and its development pathway.

The observation of different soil horizon sequences suggested that polygenetic factors were a component of the chronosequence. The horizon sequence of the oldest soils indicated development during a drier climate than present and a greater content of loess than the debris flow dominated soils.

The recent fan activity has produced a more complex situation on the temporally distributed surfaces. Buried surfaces have resulted, imposing a time transgressive relationship (refer chapter 3.2.2), where the soils were subjected to cessation at different times. The degree by which the soil was buried (discussed in chapter 7.2.2) influenced profile development. This was evident in the soil chemistry.

7.2.5 Selected soil chemical properties.

Selected soil chemical properties were used in the establishment of the soil development sequence, to assist with soil classification and assess soil fertility.

Soil pH showed a general decrease with increased soil age. Lower values were also associated with poorly drained soils (e.g. RT2).

Phosphorus values were very low in the B horizons of all profiles. This was interpreted as an indication of greater weathering and leaching (Walker and ~~Sykes~~ Syers, 1976). Very high topsoil values were due to the addition of younger less weathered sediments.

Oxalate extractable aluminium and iron increased with soil age, however in the poorly drained profile (RT2), values for iron were very low. This was attributed to the reducing conditions in which the formation of poorly crystalline iron oxides, primarily ferrihydrite is prevented.

Cation exchange values coincided with changes in particle size and organic carbon as suggested by Molloy and Blackmore (1974). A slight catenary effect was indicated by high Ca^{2+} values in profiles occupying the fan toe region.

Base saturation values decreased as soil age increased. The topsoil values for all profiles were very high due to the addition of younger sediments.

7.2.6 Comparision with other soils.

Soil development sequences on fans of different environments were discussed in chapter 3.4.

Soils of the Bullock Creek fan were compared with these sequences (see Table 7.2). Where possible absolute dates were assigned to each soil.

Soils of the Waimakariri floodplain (Suggate, 1958; Cox and Mead, 1963; New Zealand Soil Bureau, 1967; Basher, Hicks, McSaveney and Whitehouse, 1981) provided a comparable sequence of soils.

Table 7.2. The comparision of soil development sequences on fans with the Bullock Creek fan.

Study reference	Bullock Creek fan	Cox and Mead (1963)	Eggleston (1989)	Kesel and Spicer (1985)
Environment	Temperate	Temperate	Temperate	Humid/Tropical
Soil or horizon sequence (estimated age)				A.B.C (65-45 thy B.P.)
	Soil profile form 1 (Late Pleistocene)	Lismore (25-18 thy B.P.)		
	Soil profile form 2 (mid-early Holocene)			
	Soil profile form 3 (mid-early Holocene)			A.Bt.C (~7000 years)
		Templeton (10-3 thy B.P.)		
	Soil profile form 4 (late Holocene)		Cass	
		Waimakariri (late Holocene)		
	Soil profile form 5 (late Holocene)		Snowgrass	
		Selwyn (<300 years)		
	Soil profile form 6 (<100 years)		Tasman	A.C.2C (<100 years)

The temperate studies in Table 7.2 indicated similar rates of weathering and horizon development to those observed in this sudy. The development of soils in the humid/tropical environment did not seem significantly different to those of the temperate environment.

Comparisons between selected chemical data from this study and that of other fan soils of the region from Eggleston (1989) and New Zealand Soil Bureau (1967, 1968) highlight both similarities and differences between the fan environments.

The Tasman, Snowgrass and Cass soils (Eggleston, 1989) showed similarities with the soils formed in debris flow deposits. Soil pH, organic carbon and base saturation were compared.

All pH values were slightly to moderately acid. Topsoil organic carbon values were higher for the Cass Basin fan soils whereas base saturation values were generally lower. These features may be attributed to different agricultural regimes and a greater degree of soil development in the Cass Basin fan soils.

Chemical data from the Selwyn, Waimakariri and Eyre soils (New Zealand Soil Bureau, 1967, 1968) were compared with similar aged soils from this study. The soil chemical data of the Selwyn soil was comparable to that of Soil profile form 1. Soil pH values were slightly higher, ranging between 6.6 and 6.8. Organic carbon values displayed a similar trend, being high in the topsoil and decreasing rapidly with depth. Phosphorus (H_2SO_4 extractable) values were high. These compared with very high values for the CM4 profile (SPF1), which may have been a result of chemical differences in original debris mantle or a reduction in phosphorus (H_2SO_4 extractable) due to increased weathering. Lower base saturation values in the lower Selwyn soil supported the idea of increased weathering compared with the young Bullock Creek fan profile (CM4). The soil chemical data was similar to the values obtained for profile CM3 (SPF2), pH values were again slightly higher compared with those of the Bullock Creek soil and base saturation values were lower.

The soil chemical values for the Eyre soil were generally the same as for profile RT1 (SPF3). The main difference was the higher base saturation values for the surface horizons of RT1. This highlighted the aggrading nature of the Bullock Creek fan.

7.2.7 Classification.

The six simple soil profile forms were fully classified according to the New Zealand soil classification system (Hewitt, 1992) and to the suborder level using Soil Taxonomy (Soil Survey Staff, 1975). These are given in Table 7.3.

Table 7.3. Classification of the soil profile forms encountered on Bullock Creek fan.

Simple soil profile form	1	2	3	4	5	6
New Zealand soil classification (Hewitt, 1992)	Typic Fluvial Recent Soil	Typic Fluvial Recent Soil	Pallic Orthic Brown Soil	Mottled Orthic Brown Soil	Acid Mesic Organic Soil	Mottled Fragic Pallic Soil
Soil taxonomy (Soil survey staff, 1975)	Fluvents	Fluvents	Ocrepts	Aquepts	Hemists	Aquepts

The recent soils formed predominantly in debris flow deposits were classified as Fluvial Recent Soils. These soils occur in sediments deposited by flowing water. This definition does not therefore encompass soils resulting from deposition by debris flow. Debris flow is a type of mass movement. Several specific features characterize these soils.

They have very high bulk densities (greater than 1.8 g/cm^3), resulting from initially high flow densities, (~ 2.0 T/m^3 as stated in chapter 4.2.2). Bulk density often further increases as the soil matrix becomes more compact with continued soil development. Implications include, a change in the soil development pathway, limited solute movement through the soil profile and rooting difficulties for plants.

Another important factor of these soils is their multisequal nature. This is not accounted for in the New Zealand soil classification of Hewitt (1992). Multisequal soils differ from unisqual soil soils in that they effectively contain buried nutrient reserves (previous topsoil horizons that have subsequently been buried). These proved a valuable source of nutrients for deep rooting plants. Aggrading soil profiles may also rejuvenate the nutrient status of an otherwise low nutrient status soil. These features separate them from unisequal soils and on landforms such as fans where they predominate and should be classified separately.

7.3 Soil distribution and development models.

7.3.1 Microtopography and sedimentary facies.

Within the Holocene geomorphic surfaces both debris flow and sheet flood facies were identified.

The debris flow facies were thick and uniformly shaped. Unisequal soil profiles (simple soil profiles) dominated the central regions of the deposits or where deposition occured in the deeply incised channels. Multisequal (aggrading and composite soil profiles formed in the more shallow edges of the deposits (Figure 7.3.).

The sheet flood facies consisted of thinner and more variable layers. Multisequal soil profiles were dominant, with composite soil profiles forming in the thicker layers and aggrading soil profiles where deposits were thin (see Figure 7.3.).

7.3.2 Idealised changes in multisequal soils.

In the early stages of soil development buried soil horizons and rudimentary soil horizons are easily recognised in multisequal soil profiles. As the soils age and development continues recognition of buried and rudimentary horizons may be lost, resulting in a soil profile with an apparently simple horizon sequence.

Figure 7.4 represents idealised changes in multisequal soil profiles with increasing soil development. With increasing age and soil development aggrading soil profiles become characterized by a thickened A horizon whereas in composite soil profiles the identity of the "buried" A horizon is lost and the underlying horizons "weld" to form a thickened B horizon.

Figure 7.3. An idealised representation of the soil pattern in relation to microtopography and sedimentary facies.

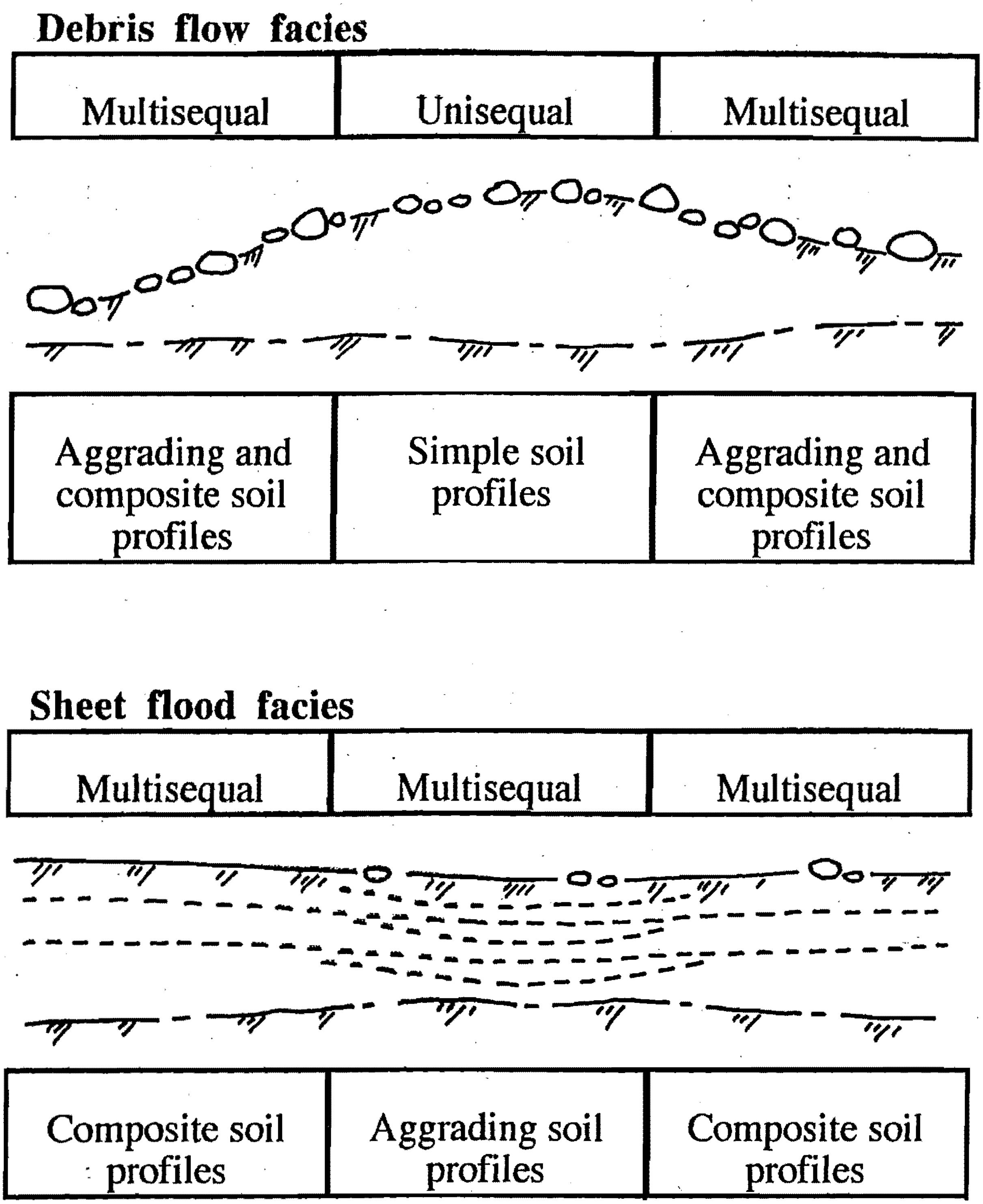
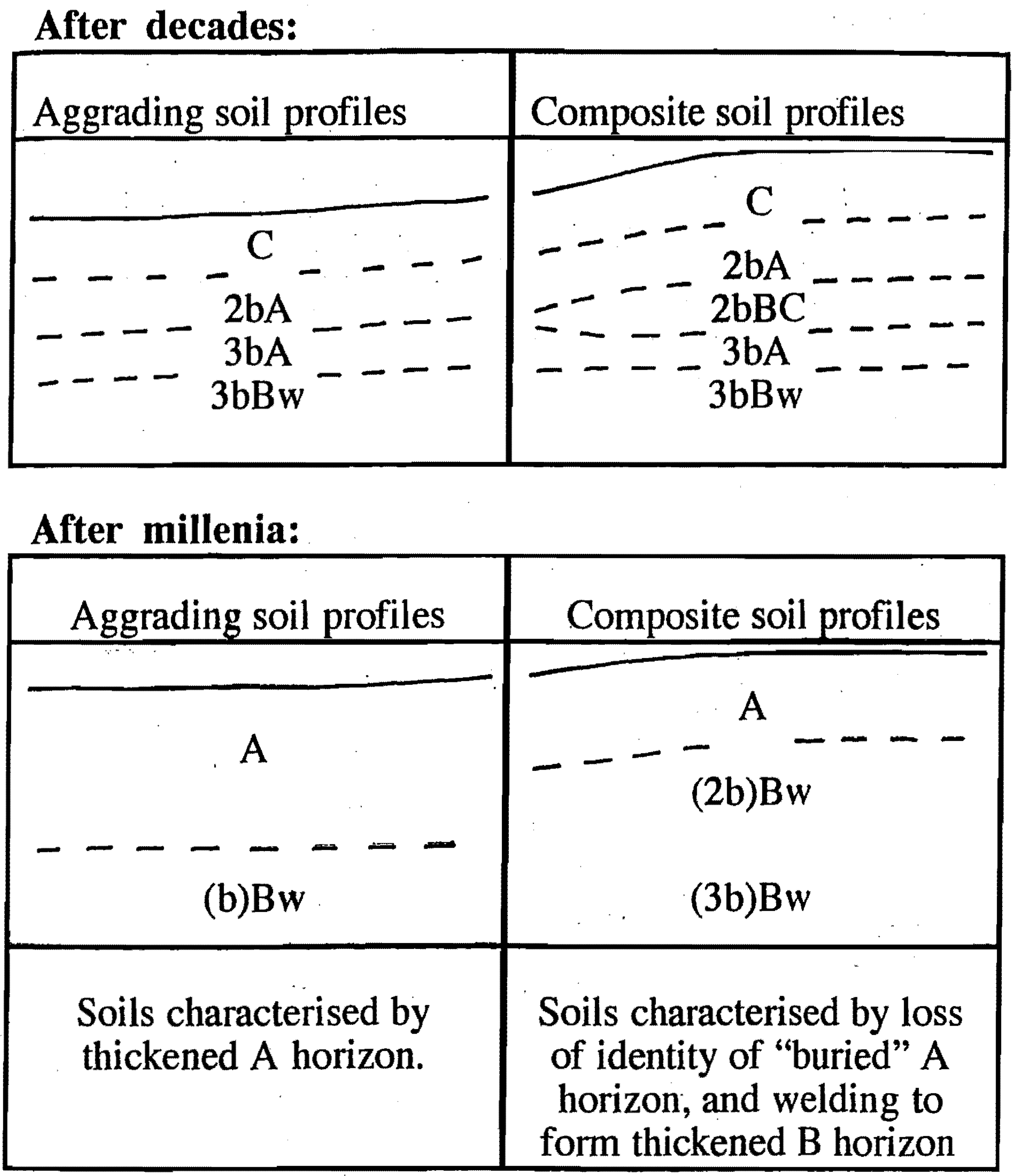


Figure 7.4. Idealised changes in multisequal soil profiles with increasing soil development and age.



7.3.3 Interpretation of fan activity using soil stratigraphy.

The idealised simplifications and loss of horizon identity shown in chapter 7.3.2 was an important factor to be considered when assessing depositional and erosional events recorded in the soil stratigraphy. At an early stage of development the soil stratigraphy may closely represent the history of events but limitations in assessing these events using the soil stratigraphy became increasingly difficult with increased soil age. This was more pronounced when events were closely spaced in time and or resulting deposits were thin and multisequal soil profiles dominated.

A key factor in assessing the history of activity using soil stratigraphy was the length of stability between successive events.

Stratigraphy on the Bullock Creek fan was dominantly controlled by the distribution and intervals separating debris flow episodes. It was found that these factors determined the degree of soil development and therefore the ease with which soil stratigraphic techniques could be used to interpret soil stratigraphy on the fan. These limitations are outlined in Table 7.4.

Table 7.4. Limitations on the use of soil statigraphy in this study.

Period of stability	Short (less than 100 years)	Long (greater than 100 years)
Soil development	Minimal; development of A horizon only	Development of A and at least a BC horizon
Stratigraphic recognition	Texture and bedding of sediments, recognition of bedding sequences and contacts Sediment stratigraphy > Soil stratigraphy	Buried, exhumed and surface soils, soil development sequences Soil stratigraphy > Sediment stratigraphy
Limitations	Interpretation of beds as being from a single episode or multiple closely timed episodes	Loss of sensitivity with continued soil development

7.4 The impact of debris flow activity.

7.4.1 Physical disturbance.

The debris flows on Mount Thomas are highly destructive in the drainage basin, the valley floor and on the fan itself. Pierson (1980b), documented the resulting destruction of the debris flow episode of April 1978.

The presence of large debris flow related surface forms mapped on the fan, combined with personal accounts of activity described by landowners, Bill Ensor and Dixon Patterson

(Personal Communication) suggested that the debris flows were destructive as far down as the fan toe. Here they eventually stopped, depositing large lobes of coarse sediment supported by a fine matrix.

Damage included the formation of deeply incised channels, the burial of pastures and fences with sediments ranging in size from silts to boulders up to one metre in diameter (see Plate 7.2) and the uprooting and ringbarking of trees by coarse sediments.

Plate 7.2. Large boulder situated in a debris flow channel in the mid fan region.

7.4.2 Landuse.

7.4.2.1 Cultivation.

Cultivation following debris flow episodes was more favourable on the sheet flood sediments due to their finer texture and more even microtopography. They contained a higher percentage of finer sediments such as clays and silts compared with the coarser debris flow sediments which had a matrix dominated by sands. Soils formed in the finer sediments showed greater water retention than their coarser counterparts. However, it was noted that water preferentially moved down the fan within the coarse debris flow lobes deposited on the previous fan surface.

7.4.2.1 Soil fertility.

Soil chemical analyses showed the fertility of the recent soils to be closely comparable to those of the late Holocene soils. The selected soil chemical properties examined were pH, organic carbon, base saturation and phosphorus (H_2SO_4 extractable). The results are presented in Table 7.5.

Soil pH values for both soils lay within a suitable range for pasture growth. Rapid accumulation of organic matter in the Recent Soil to a level comparable to that of the older Brown Soil was indicated by the organic carbon values. Very high base saturation and phosphorus (H_2SO_4 extractable) in the Recent soil both indicated high initial soil fertility, a reflection of recent sediment addition. The high fertility of the younger soils suggested the continued addition of thin layers of sediment actes as a natural fertiliser, replentishing soil nurtrients lost via leaching and weathering. Similar levels of fertility were a feature of the upper horizons of older aggrading soils.

Although debis flow activity has resulted in a vast amount of geomorphic modification and disrupted established farmland, re-establishment of pastures has been successful due to the high fertility of recently deposited sediments. Plate 7.3 shows re-established pastures surrounding an abandoned channel containing debris flow lobes.

Plate 7.3. Re-established pastures on recent debris flow deposits.

Table 7.5. Selected soil chemical properties to illustrate the fertility of late Holocene aged soils.

pH		**Organic carbon (%)**		**Base saturation (%)**		**Phosphorus-H_2SO_4 extractable (mg/100g)**	
Fluvial Recent Soil (mid fan - 20 to 40 years old)							
A	**C**	**A**	**C**	**A**	**C**	**A**	**C**
5.4	6.1	2.8	0.4	95	87	59	34
Stony Brown Soil (mid fan - late Holocene?)							
A	**Bw**	**A**	**Bw**	**A**	**Bw**	**A**	**Bw**
5.1	5.6	3.0	0.4	50	38	30	16

It is not expected that all the Recent Soils were of the same fertility. Those formed in the finer deposits (predominantly hyperconcentrated flow related deposits), provided a more easily available source of nurtrients than the coarser textured soils, due to the higher surface to volume ratio of particles.

Multisequal soils provided vegetation with a buried source of organic matter in the form of buried A and O horizons. This should be considered as of special importance with deep rootinig plants which are able to utilise these buried sources of nutrients.

CHAPTER 8
CONCLUSIONS

CHAPTER 8.0 CONCLUSIONS.

1. Three major periods of fan aggradation were recognised:

   (i). The oldest surface, now buried by 2.5 metres of loess was of late Pleistocene age.

   (ii). A mid to early Holocene period of sedimentation was indicated by surfaces underlain by Stony Brown Soils formed in mixed gravelly and silty sediments.

   (iii). The most recent period of sedimentation has been occurring since the early 1900's, with several phases of deposition recognisable in the soil stratigraphy (ie. Fluvial Recent Soils with aggrading and composite soil profile forms).

2. Multisequal soils were predominant on the fan, reflecting the aggrading nature of the fan surfaces.

3. Where events were closely spaced in time or soil development was minimal the relationship between surfaces was difficult to assess using soil stratigraphic techniques.

4. With increasing surface age, "welding" of soil morphological features in aggradational and composite soil profiles obscures the recognition of closely timed phases or thin bedded sequences of fan aggradation.

5. Multisequal soils differ from their unisequal counterparts and should be identified separately, in the field (mapping) and when classified.

6. On the active aggradational surfaces debris flow and sheet flood deposits predominated.

7. There has been significant sediment aggradation in the region of the valley floor and the fan head since the last phase of fan sedimentation in 1978.

8. Recent debris flow and sheet flood deposits displayed significant aggradation in the mid and lower fan regions.

9. Soil development and re-establishment of pastures on the aggrading fan surfaces has been enhanced by the natural fertility of the sediments.

10. Sheet flood deposits produced more easily cultivated soils because of their finer and uniform textural properties.

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APPENDIX A

LEGEND FOR SOIL MORPHOLOGICAL DESCRIPTIONS.

Horizon Boundaries

Distinctness
sh-sharp
abr-abrupt
clr-clear
gr-gradual

Shape
sm-smooth
wy-wavy
irr-irregular

Moist Colour
(refer Munsell Soil Colour Charts)

Mottles

Abundance
fw-few
co-common
ma-many
ab-abundant

Size
f-fine
md-medium
c-coarse

Contrast
ft-faint
di-distinct
pr-prominant

Texture

Fine Earth
s-sand
ls-loamy sand
sl-sandy loam
l-loam
zl-silt loam
cl-clay loam
h-humic

Skeletal Texture

Volume
slt-slightly
m-moderately
v-very

Material
grv-gravelly
st-stony
bd-bouldery

Shape
a-angular
sa-subangular
sr-subrounded
r-rounded

Weathering
fr-fresh
slt-slightly
m-moderately
str-strongly

Consistence

Strength
lo-loose
w-weak
fm-firm
str-strong

Failure
bt-brittle
sd-semideformable
d-deformable
sfd-slightly fluid
mfd-moderately fluid
fd-fluid

Stickiness
ns-non
ss-slightly
ms-moderately
vs-very

Plasticity
np-non
sp-slightly
mp-moderately
vp-very

Structure

Grade
sg-single grained
mass-massive
wk-weak
m-moderate
str-strong

Size
vf-very fine
f-fine
md-medium
c-coarse

Type
cr-crumb
gr-granular
nt-nut
bk-blocky
prs-prismatic

Packing
(refer chapter 2.6.5)
P1
P2
P3
P4

Concretions

Abundance and *Size*
(refer ***Mottling***)

Type
Fe, Mn (oxidic)

Cutans

Kind
org-organic
Fe, Mn (oxidic)

Abundance and *Contrast*
(refer ***Mottling***)

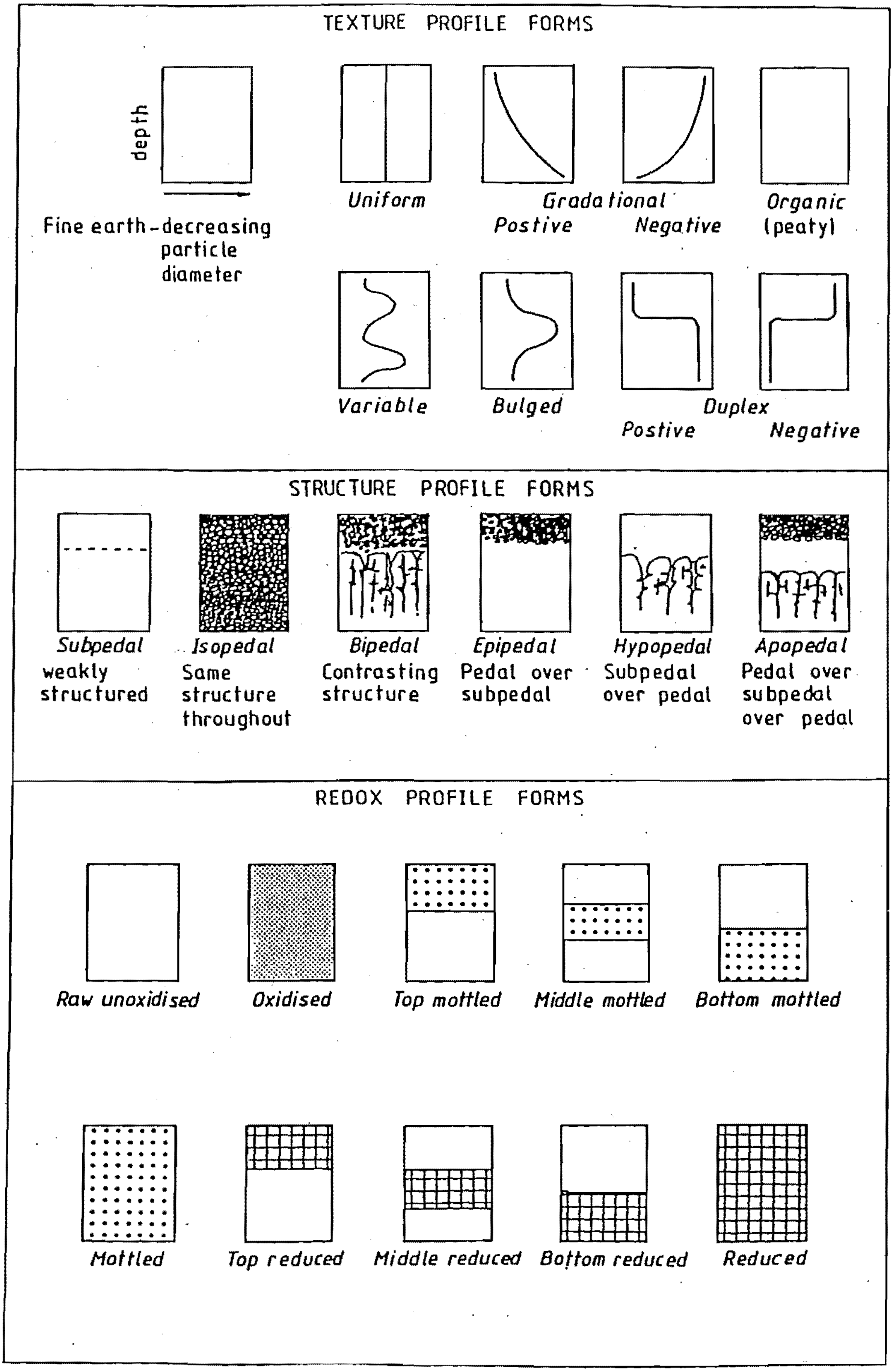
Continuity
p-patchy
dc-discontinuous
c-continuous

Roots

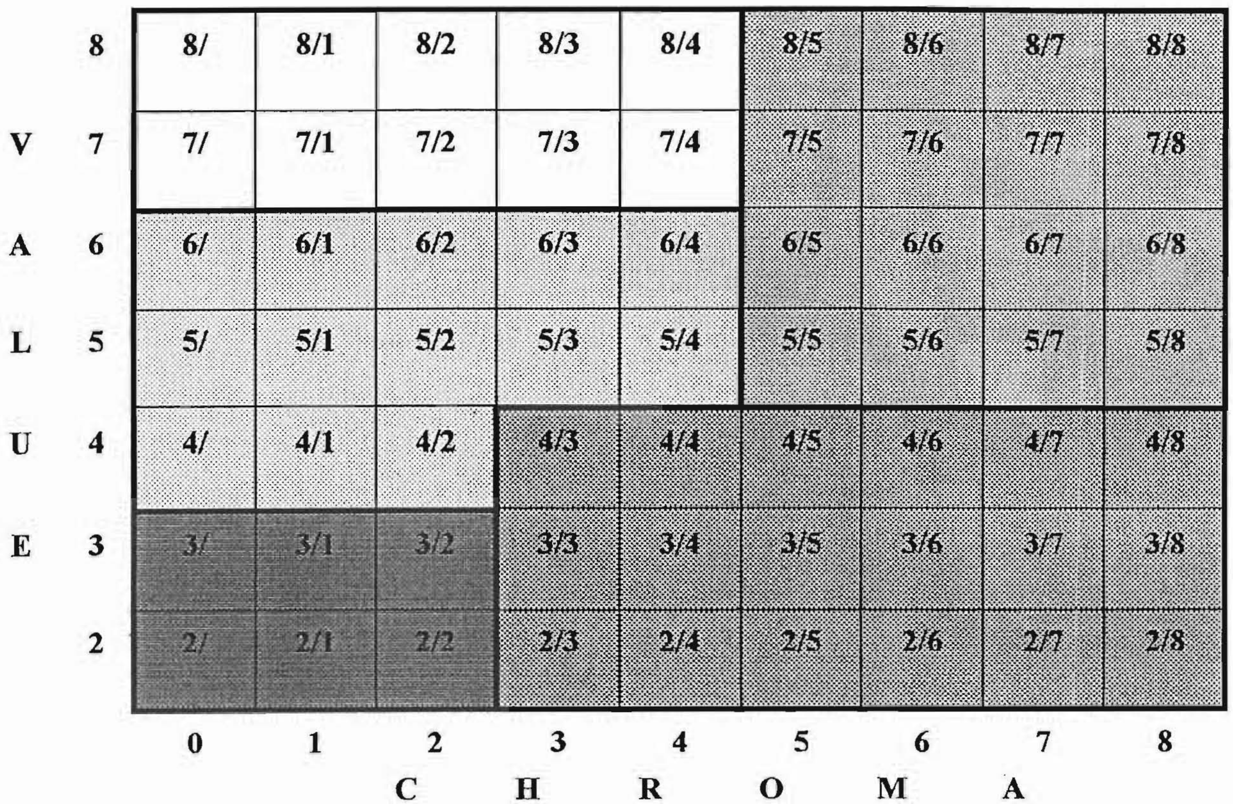
Abundance
(refer ***Mottling***)

Size
vf-very fine
f-fine
md-medium
c-coarse

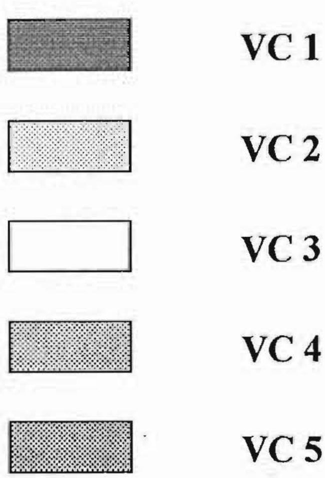
LEGEND FOR PROFILE FORMS.



LEGEND FOR VALUE/CHROMA COLOUR RATING GROUPS.
(After Northcote, 1979).



VALUE/CHROMA GROUP (VC).

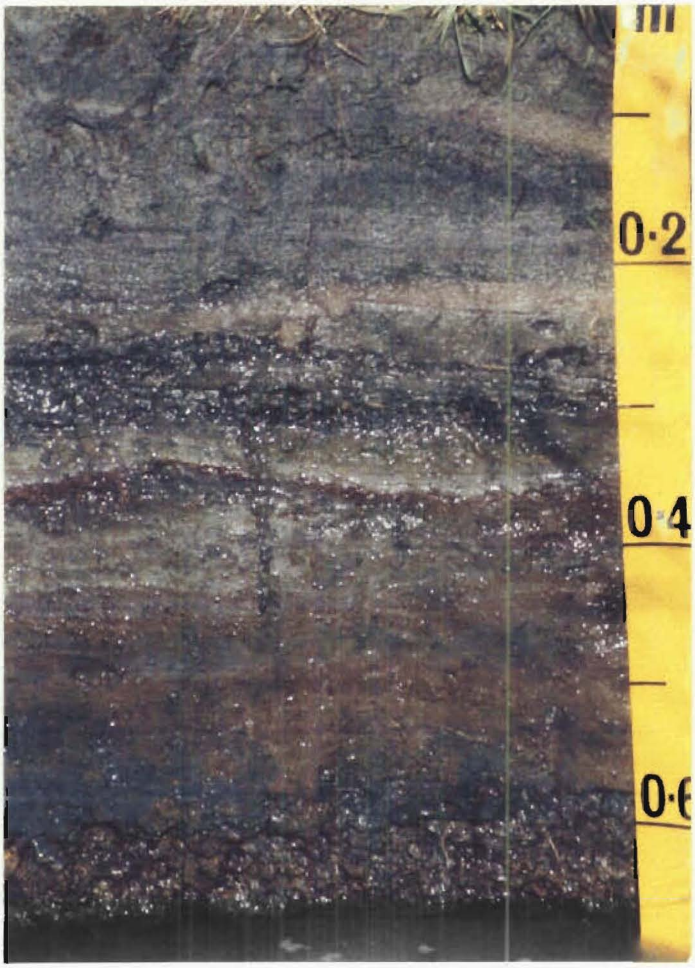


APPENDIX B

LH1. SOIL PROFILE DESCRIPTION.

Soil Horizon	Ah	C1	C2	2C	3C	4bO	5bC	6bC
Depth (cm)	0-7	7-16	16-24	24-29	29-33	33-35	35-58	58-80
Boundary								
distinctness	abr	abr	abr	cl	sh	cl	cl	
shape	wy	wy	sm	wy	wy	wy	wy	
Moist Colour	7.5GY 3/1	10GY 3/1	7.5GY 4/1	10GY 3/1	5GY 4/1	7.5GY 3/4	7.5YR 3/4	lith
Mottling								
abundance								
size								
contrast								
colour								
Texture								
Skeletal								
size and volume		v.grv		v.grv		peat	peaty	v.grv
shape		a		a				sa
weathering		fr		fr				fr
Fine	ls	s	ls	s	zl		zl	zl
Consistence								
Fine								
strength	lo	lo	w	lo	w		w	low
failure			br	sd	d		sd	sd
stickiness								
plasticity								
Skeletal								
packing		P2		P2				P2
Structure								
grade	sg/mass	sg	mass/sg	sg	mass		mass	mass
size								
type								
Concretions								
abundance								
size								
type								
Cutans								
kind								
abundance								
contrast								
type								
Roots								
abundance	ab	co	fw	fw	co	ab	ma	co
size	vf	f	f	vf	f	f	vf	vf
Field pH	5-5.5	5.0	5.0	5.0	4.5-5.0	4.0	4.5	4.5-5.0

LH1. PLATE OF SOIL PROFILE.



LM1. SOIL PROFILE DESCRIPTION.

Soil Horizon	A	2bAg	2bABg	2bBr	2bBrg	2bBx1	2bBx2
Depth (cm)	0-20	20-30	30-54	54-62	62-85	85-167	167-220
Boundary							
distinctness	gr	gr	cl	cl	gr	df	gr
shape	wy	wy	wy	irr	irr	irr	wy
Moist Colour	10YR 3/2	10YR 4/2	10YR 4/2	2.5Y 8/4	5Y 7/2	10YR 6/6	10YR 7/6
Mottling							
abundance	fw	ma	ma	ab	ab	ab	ab
size	f	f	f	md	c	c	md
contrast	ft	di	di	di	pr	pr	di
colour	5YR 5/8	10YR 6/6	10YR 6/6	7.5YR 5/8	10YR 6/6	10YR 6/4	7.5YR 6/4
Texture							
Skeletal							
size and	slt.grv	slt.grv					
volume		m.st					
shape	a	a					
weathering	fr	fr					
Fine	zl	zl	zl	zl	zl	zl	zl
Consistence							
Fine							
strength	fm	fm	fm	fm	w	w	fm
failure	sd	sd	sd	sd	br	sd	sd
stickiness							
plasticity							
Skeletal							
packing	P3	P2-P3					
Structure							
grade	m	str	str	str	mass, str	str	mass
size	vf	vf	f	f	md	c	
type	nt	bk	bk	bk	bk	prs	
Concretions							
abundance		fw	fw, co	fw	co	co	
size		vf	f	f	f	f	
type		Fe	Fe, Mn	Fe	Mn	Mn	
Cutans							
kind				Fe	Fe	Mn	Mn
abundance				fw	fw	fw	fw
contrast				di	di	di	di
continuity				pt	pt	pt	pt
Roots							
abundance	ma	co	fw	fw			
size	vf	vf	vf	vf			
Field pH	5.0-5.5	5.5-6.0	5.5-6.0	5.5	5.5	5.5	5.5-6.0

Auger description

LM1. SOIL PROFILE DESCRIPTION.

Auger description

Soil Horizon	2Bbx3	3bBxg1	3bBxg2	3bBx
Depth (cm)	220-280	280-300	300-330	330-340+
Boundary				
distinctness				
shape				
Moist Colour	10YR 6/6	2.5Y 7/3	10YR 7/4	2.5Y 7/4
Mottling				
abundance	ma	ma	ma	fw
size	f	f	md	f
contrast	di	di	ft	ft
colour	7.5YR 5/6	7.5YR 5/8	10YR 6/6	2.5Y 7/6
Texture				
Skeletal				
size and	slt.grv	slt.grv	slt.grv	slt.grv
volume	slt.st	slt.st		
shape	a	a	a	a
weathering	fr	fr	a	a
Fine	zcl	sl	ls	sl
Consistence				
Fine				
strength				
failure				
stickiness				
plasticity				
Skeletal				
packing				
Structure				
grade				
size				
type				
Concretions				
abundance				
size				
type				
Cutans				
kind				
abundance				
contrast				
continuity				
Roots				
abundance				
size				
Field pH	5.5	5.5	6.0	6.0

LM1. PLATE OF SOIL PROFILE.

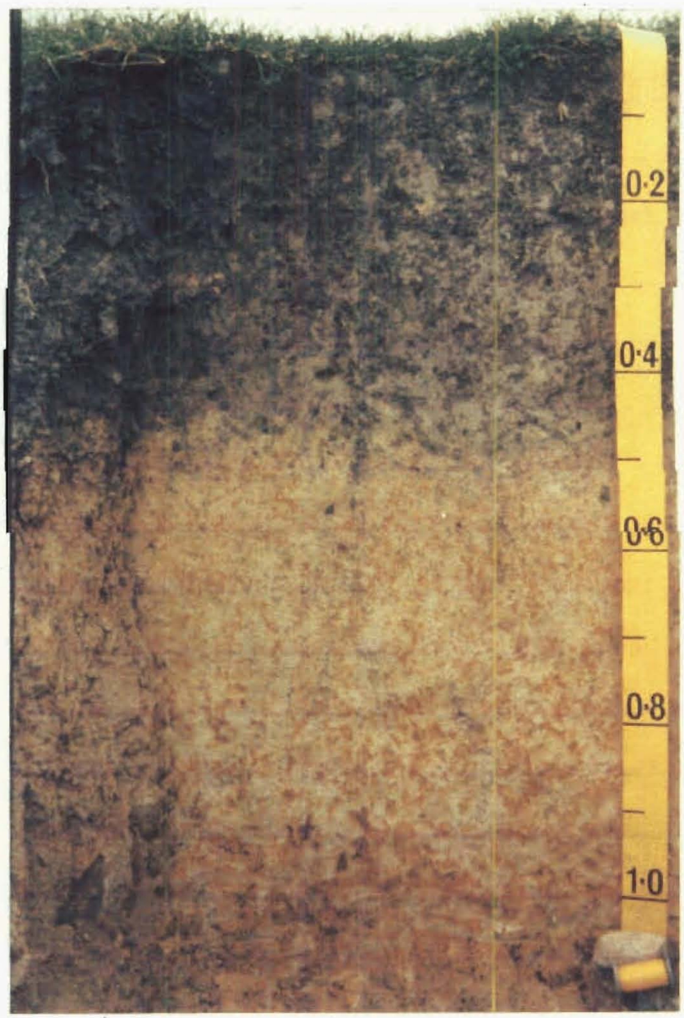
LM2. SOIL PROFILE DESCRIPTION.

Soil Horizon	A	2bAg	2bABg	2bBr	3bB	4bBx	5bBx
Depth (cm)	0-20	20-43	43-55	55-110	110-146	146-228	228-232+
Boundary							
distinctness	abr	gr	gr	clr	abr	abr	
shape	sm	wy	wy	irr	wy	wy	
Moist Colour	2.5Y 3/2	2.5Y 3/2	2.5Y 3/2>7/4	2.5Y 7/2	10YR 7/6	10YR 6/4	2.5Y 7/4
Mottling							
abundance		fw	ma	ab	fw	fw	ab
size		f	f	md	f	f	c
contrast		ft	di	pr	ft	ft	di
colour		7.5YR 6/8	7.5YR5/8	7.5YR5/8	7.5YR5/8	10YR 6/8	7.5YR 6/8
Texture							
Skeletal							
size and volume	slt.grv				v.grv, m.st		
shape	sa				sa		
weathering	fr				slt		
Fine	sl	zl	zl	zl	sl	cl	cl
Consistence							
Fine							
strength	fm	fm	fm	w	lo	fm	fm
failure	bt	bt	bt	bt		sd	d
stickiness	ns	ns	ns	ns	ns	ss	ss
plasticity	np	np	np	np	np	sp	sp
Skeletal							
packing					P4		
Structure							
grade	m	str	str	str	sg	str	mass
size	f	f	f	vf		m.bk with	
type	nt	nt	bk	bk		c.prs	
Concretions							
abundance			fw	ma		ma	
size			f	f		f	
type			Fe	Fe		Fe	
Cutans							
kind							
abundance							
contrast							
continuity							
Roots							
abundance	ma	co	fw	fw			
size	f	f	f	f			
Field pH	5.5	5.5	5.0-5.5	5.0	5.5	5.5	5.5-6.0

LT1. SOIL PROFILE DESCRIPTION.

Soil Horizon	**A**	**AB**	**Bg**	**Cr**	**2Cr**
Depth (cm)	0-20	20-36	36-70	70-105	105-135+
Boundary					
distinctness	gr	gr	clr	clr	
shape	irr	irr	irr	irr	
Moist Colour	10YR 3/3	10YR 3/4	2.5Y 6/2	2.5Y 7/2	2.5Y 7/4
Mottling					
abundance		co	ma	ma	ma
size		f-md	md	c	c
contrast		ft	di	pr	pr
colour		10YR 5/6	10YR 5/6	10YR 5/6	10YR 6/6
Texture					
Skeletal					
size and			slt.grv	v.grv	m.grv
volume					
shape			sr	sr	sa
weathering			m	m	slt
Fine	zl	zl	sl	ls	sl
Consistence					
Fine					
strength	w	fm	fm	w	w
failure	br	br	br	br	sd
stickiness					
plasticity					
Skeletal					
packing			P2	P3	P3
Structure					
grade	m	m	m	sg	mass
size	vf	f	md		
type	nt	bk	bk		
Concretions					
abundance					co
size					f
type					Fe
Cutans					
kind					
abundance					
contrast					
continuity					
Roots					
abundance	ma	fw	fw		
size	f	vf	vf		
Field pH	5.5-6.0	5.0-5.5	5.0-5.5	5.5	5.5

LT1. PLATE OF SOIL PROFILE.



CM2. SOIL PROFILE DESCRIPTION.

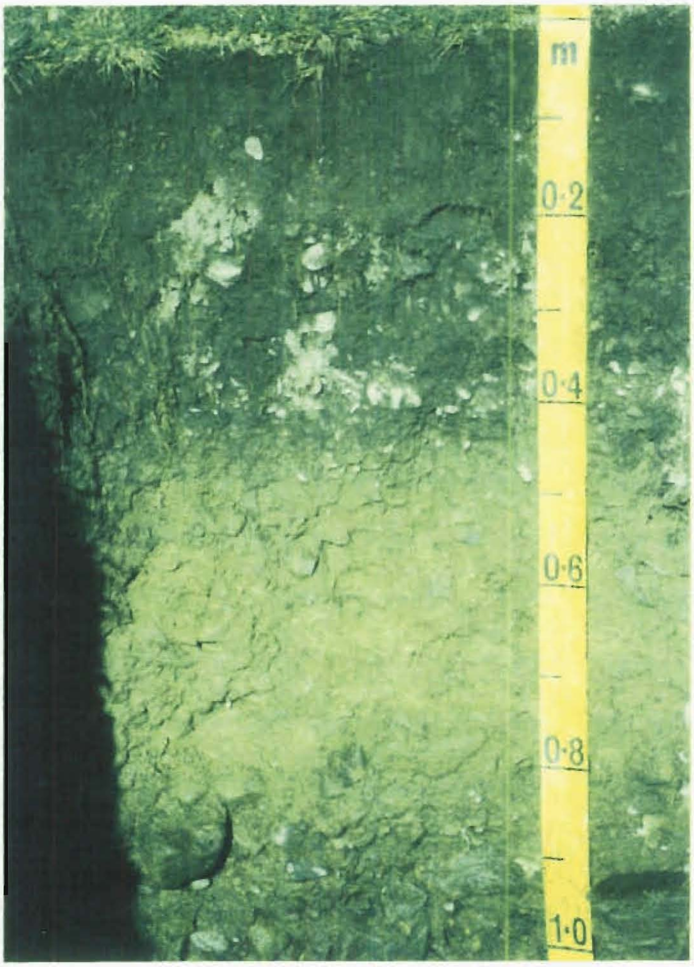
Soil Horizon	**Ac1**	**Ac2**	**2C1**	**2C2**	**3bA**	**4bC**	**5bC**
Depth (cm)	0-15	15-38	38-48	48-53	53-65	65-85	85-140+
Boundary							
distinctness	gr	abr	abr	abr	cl	cl	
shape	irr	wy	sm	wy	wy	irr	
Moist Colour	10YR 2/1	10YR 2/1	2.5Y 3/2	lith	2.5Y 4/2	5Y 3/1	5Y 3/2
Mottling							
abundance							
size							
contrast							
colour							
Texture							
Skeletal							
size and	m.grv	v.grv	slt.grv	grv	slt.grv	v.grv	v.st
volume	slt.st	m.st				m.st	m.bd
shape	sa	sa	sa	sa	sa	sa	sa
weathering	fr	fr	fr	fr	fr	fr	fr
Fine	ls	s	ls		ls	s	s
Consistence							
Fine							
strength	lo	lo	w	lo	w	lo	lo
failure			br		br		
stickiness							
plasticity							
Skeletal							
packing	P2	P2	P3	P1	P3	P3	P3
Structure							
grade	w	sg	w	sg	w	sg	sg
size	vf		vf		vf		
type	nt		nt		bk		
Concretions							
abundance							
size							
type							
Cutans							
kind							
abundance							
contrast							
continuity							
Roots							
abundance	ab	ma	fw	fw	c	fw	fw
size	vf-f	vf-f	f	vf	vf	vf	f
Field pH	5.5	5.5	5.0	5.5	5.5-6.0	6.0	6.5

CM2. PLATE OF SOIL PROFILE.

CM3. SOIL PROFILE DESCRIPTION.

Soil Horizon	**A**	**2bA**	**2bAB**	**2bBC**	**3bC**	**4bC**
Depth (cm)	0-20	20-37	37-50	50-80	80-120	120-140+
Boundary						
distinctness	cl	cl	abr	cl	cl	
shape	wy	wy	wy	wy	wy	
Moist Colour	10YR 2/2	10YR 3/1	2.5Y 3/1	2.5Y 5/3	2.5Y 4/3	2.5Y 4/4
Mottling						
abundance						
size						
contrast						
colour						
Texture						
Skeletal						
size and	slt.grv	m.grv	m.grv	m.grv	m.grv	v.grv
volume			m.st	v.st	v.st	m.st
shape	sa	sa	sa	sa	sa>sr	sa>sr
weathering	fr	fr	fr	fr	fr	fr
Fine	sl	sl	sl	ls	ls	ls
Consistence						
Fine						
strength	w	w	w	w	lo	lo
failure	sd	sd	br	br		
stickiness						
plasticity						
Skeletal						
packing	P2	P2		P3	P3	P3
Structure						
grade	w	w	w	w	sg	sg
size	vf	vf	vf	vf		
type	nt	nt	nt	nt		
Concretions						
abundance						
size						
type						
Cutans						
kind						
abundance						
contrast						
continuity						
Roots						
abundance	ab	ab	co	fw		
size	vf	vf	f	f		
Field pH	6.0	5.5	5.5	5.5	5.5-6.0	6.0

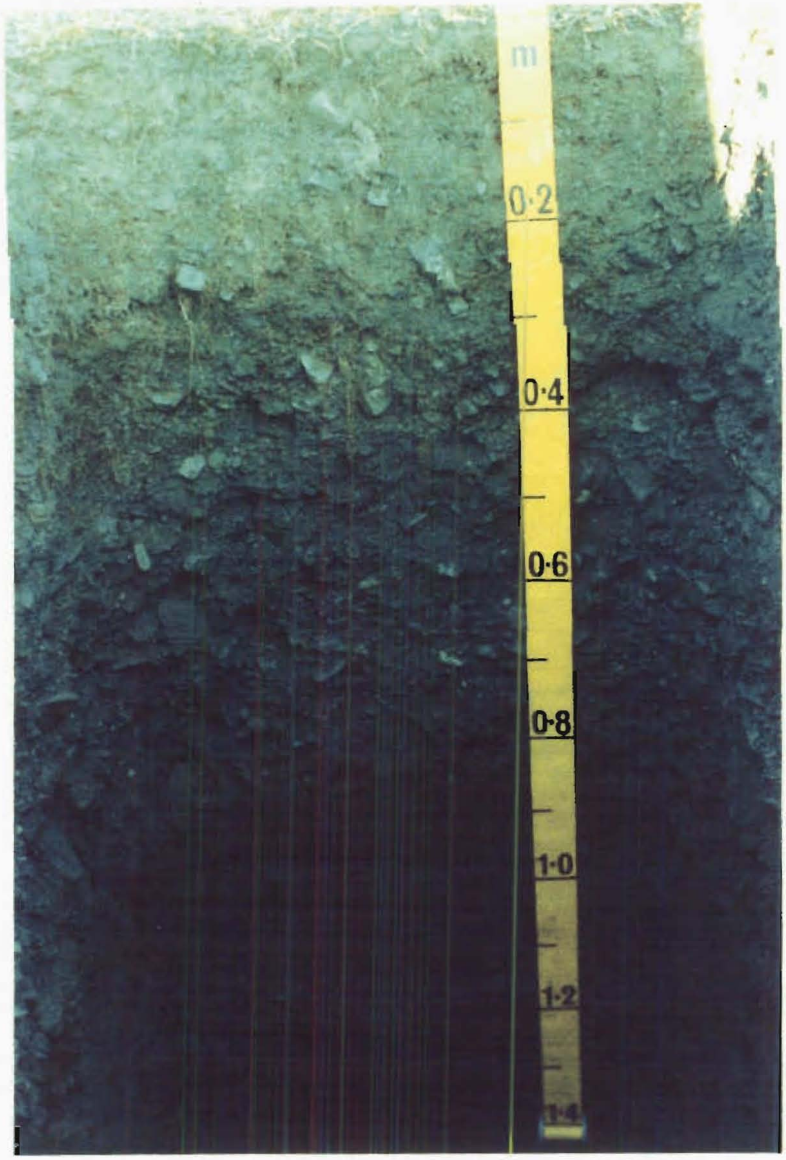
. **PLATE OF SOIL PROFILE.**



CM4. SOIL PROFILE DESCRIPTION.

Soil Horizon	**A**	**C**	**2bAg**	**3Cg**	**4C**	**5C**	**6C**
Depth (cm)	0-20	20-60	60-78	78-95	95-112	112-150	150-160+
Boundary							
distinctness	cl	gr	gr	abr	abr	cl	
shape	wy	irr	irr	wy	sm	wy	
Moist Colour	2.5Y 4/2	2.5Y 3/2	2.5Y 4/1	2.5Y 4/1	5Y 4/1>3/2	5Y 3/1	7.5YR 4/2
Mottling							
abundance			ab	ma			
size			md	f			
contrast			di	ft			
colour			7.5YR 4/6	7.5YR 5/6			
Texture							
Skeletal							
size and	m.grv	m.grv	slt.grv	m.grv	m.grv	slt.grv	m.grv
volume	slt.st	m.st			slt.bd		m.st
shape	sa	sa	sa		sr	sr	sa
weathering	fr	fr	fr	fr	fr	fr	fr
Fine	sl	ls	ls	ls	s	ls	ls
Consistence							
Fine							
strength	w	lo	w	w	lo	w	lo
failure	sd		sd	sd		sd	
stickiness							
plasticity							
Skeletal							
packing		P3	P3		P2	P3	P3
Structure							
grade	w	sg	w	mass to w	sg	mass to w	sg
size	f		f	f		f	
type	cr		bk	bk		bk	
Concretions							
abundance							
size							
type							
Cutans							
kind							
abundance							
contrast							
continuity							
Roots							
abundance	ab	ab					
size	vf-f	vf-f					
Field pH	5.0	5.5	5.5-60	6.0	6.0-6.5	7.0	7.5

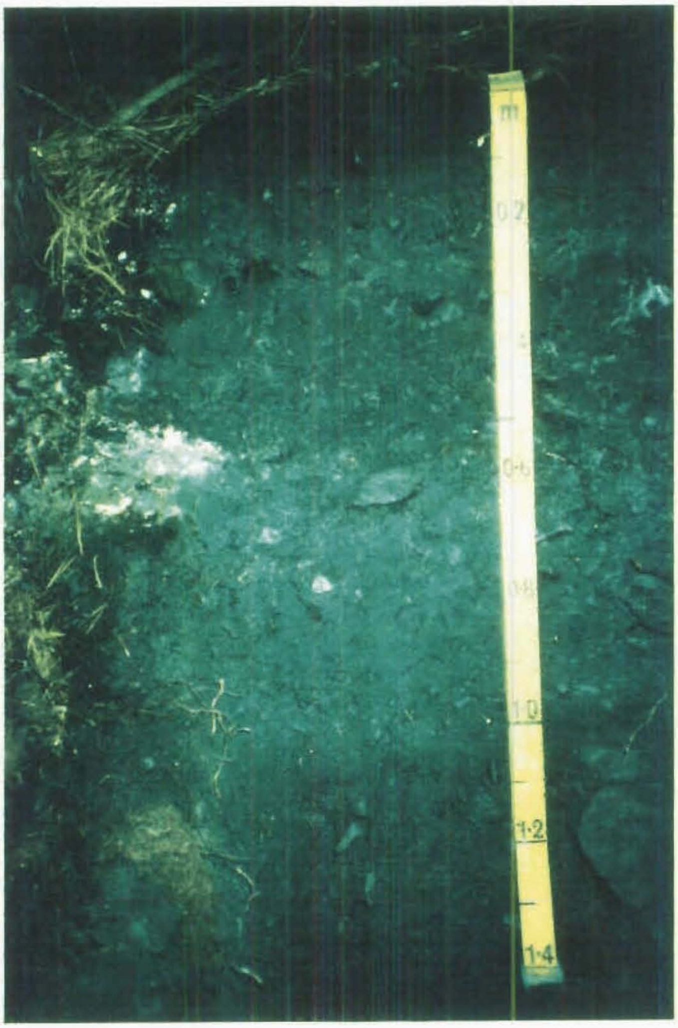
CM4. PLATE OF SOIL PROFILE.



RH1. SOIL PROFILE DESCRIPTION.

Soil Horizon	A	C	2C	3C1	3C2	4C
Depth (cm)	0-5	5-42	42-76	76-104	104-122	122-140+
Boundary						
distinctness	clr	gr	clr	clr	gr	
shape	irr	irr	wy	wy	wy	
Moist Colour	7.5YR 3/2	7.5YR 4/1	7.5YR 4/1	5Y 3/1	5Y 3/2	2.5Y 4/2
Mottling						
abundance						
size						
contrast						
colour						
Texture						
Skeletal						
size and	slt.grv	v.grv	m.grv	m.grv	m.grv	v.grv
volume			v.st	slt.st	v.st	m.st
shape	a	a>sa	a>sa	a>sa	sa	sr
weathering	fr	fr	fr	fr	fr	fr
Fine	sl	ls	s	ls	ls	ls
Consistence						
Fine						
strength	w	w	lo	lo	lo	lo
failure	sd	sd				
stickiness						
plasticity						
Skeletal						
packing		P4	P3	P3	P4	P3
Structure						
grade	w	sg	sg	sg	sg	sg
size	f					
type	cr					
Concretions						
kind						
abundance						
contrast						
continuity						
Cutans						
abundance						
size						
shape						
Roots						
abundance	ma	ma	ma	co	ma	fw
size	f-md	vf-md	f	md	md	f-md
Field pH	5.5	5.0-5.5	5.5	6.0	6.5	6.5

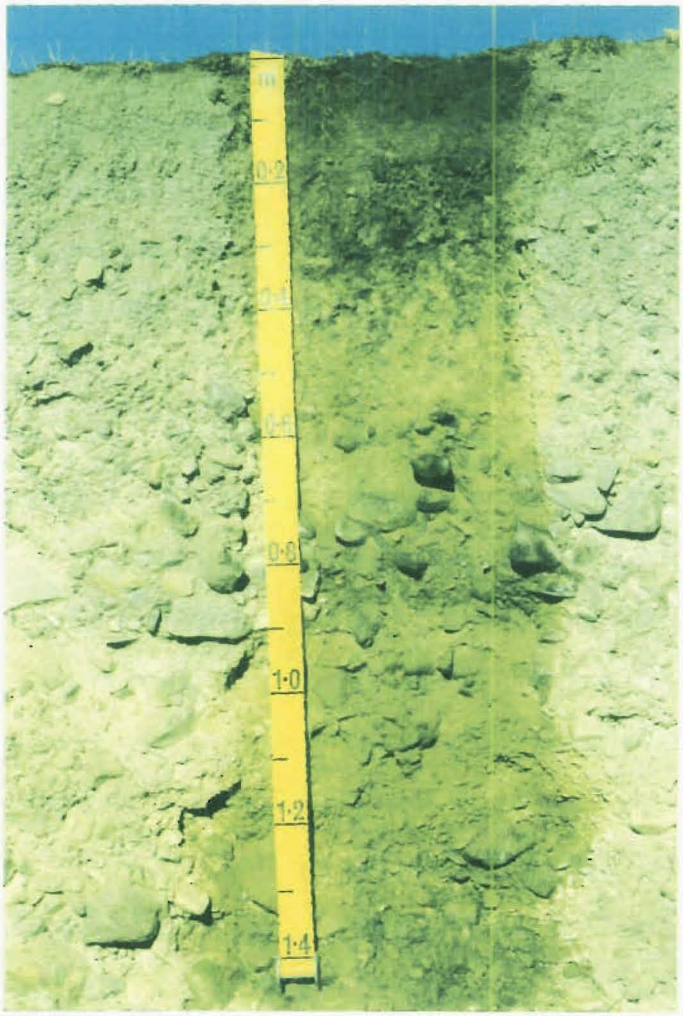
H1. PLATE OF SOIL PROFILE.



RM1. SOIL PROFILE DESCRIPTION.

Soil Horizon	**A1**	**A2**	**2bAg**	**2bBw**	**3bC**	**4bC**	**5bC**
Depth (cm)	0-14	14-33	33-46	46-67	67-88	88-115	115-140+
Boundary							
distinctness	clr	df	df	clr	abr	clr	
shape	wy	irr	irr	irr	sm	wy	
Moist Colour	2.5Y 4/1	2.5Y 3/1	2.5Y 4/1>6/4	2.5Y 5/3	2.5Y 5/3	10YR 5/2	10YR 5/2
Mottling							
abundance		co	ma	fw			
size		f	f	f			
contrast		di	di	ft			
colour		5YR 3/6	5Y 4/8	7.5YR 5/6			
Texture							
Skeletal							
size and	slt.grv	slt.grv	slt.grv	v.grv	v.grv	m.grv	v.grv
volume		m.st	m.st	m.st	m.st	m.st	m.st
shape	a>sa	a>sa	sa	sa	sa	sa	sa>sr
weathering	fr	fr	fr	fr	fr	slt	slt
Fine	sl	zl	sl	sl	sl	sl	ls
Consistence							
Fine							
strength	w	w	fm	fm	w	lo	lo
failure	br	sd	sdd	sd	br		
stickiness							
plasticity							
Skeletal							
packing	P2	P3	P3	P4	P3	P4	P3
Structure							
grade	w	m	m	m	mass	w	sg
size	f	f	f	f		md	
type	nt	nt	bk	bk		gr	
Concretions							
abundance							
size							
type							
Cutans							
kind							
abundance							
contrast							
continuity							
Roots							
abundance	ab	ma	fw	fw			
size	vf	f	f	vf			
Field pH	5.0-5.5	5.0-5.5	5.5	5.5	5.5-6.0	5.5-6.0	5.5-6.0

RM1. PLATE OF SOIL PROFILE.



RM2. SOIL PROFILE DESCRIPTION.

Soil Horizon	**A**	**2C**	**3bAg**	**3bABg**	**3bBg**	**4bC**	**5bBg**	**6bCr**
Depth (cm)	0-7	7-22	22-36	36-48	48-65	65-85	85-95	95-150+
Boundary								
distinctness	clr	abr	gr	gr	clr	abr	gr	
shape	irr	irr	wy	wy	wy			
Moist Colour	10YR 3/1	2.5Y 3/1	2.5Y 4/1	2.5Y 5/1	2.5Y 6/2	2.5Y 7/3	2.5Y 7/3	2.5Y 6/3
Mottling								
abundance		co	ab	ma	ma		ma	ab
size		f	f	md	f		f	c
contrast		f	pr	pr	di		pr	pr
colour		5YR 5/6	5YR 5/6	10YR 6/8	10YR 6/6		7.5YR 5/6	7.5YR 6/6
Texture								
Skeletal								
size and	v.grv		v.grv	v.grv	v.grv	v.grv	m.grv	slt.grv
volume	slt.st					slt.st		slt.st
shape	a>sa		sa	sr	sr	sr	sr>sa	sa
weathering	fr		fr	slt	slt	slt	slt	slt
Fine	ls	zl	zl	zl	sl	sl	sl	sl
Consistence								
Fine								
strength	lo	w	fm	fm	fm	w	w	fm
failure		sd	sd	sd	sd	br	sd	sd
stickiness								
plasticity								
Skeletal								
packing	P2		P2	P2	P3	P2	P3	P2
Structure								
grade	sg	mass	m	m	m	w	w	w
size			f	f	f	vf	f	vf
type			bk	bk	bk	nt	bk	bk
Concretions								
abundance							co	co
size							f	f
type							Mn	Mn
Cutans								
kind						Mn		
abundance						fw		
contrast						di		
continuity						dc		
Roots								
abundance	ma	co	ma	ma	co	fw		
size	f	f	f	f	f	vf		
Field pH	7.0	6.5	5.0	5.5	5.5-6.0	6.0	6.0	6.0

RM2. PLATE OF SOIL PROFILE.

RM3. SOIL PROFILE DESCRIPTION.

Soil Horizon	A	C1	C2	2C	3C
Depth (cm)	0-22	22-45	45-75	75-145	145-160+
Boundary					
distinctness	clr	gr	clr	clr	
shape	wy	wy	wy	wy	
Moist Colour	10YR 2/2	10YR 5/3	2.5Y 4/1	2.5Y 4/1	2.5Y 4/1
Mottling					
abundance					
size					
contrast					
colour					
Texture					
Skeletal					
size and	v.grv	v.grv	v.grv	m.grv, slt.st	slt.grv, v.st
volume	m.st	m.st	m.st	m.bd	slt.bd
shape	a>sa	a>sa	a>sa	a>sa	sa
weathering	fr	fr	fr	fr	fr
Fine	sl	s	s		s
Consistence					
Fine					
strength	w	lo	lo	lo	lo
failure	br				
stickiness					
plasticity					
Skeletal					
packing	P3	P2	P2	P2	P2
Structure					
grade	w	sg	sg	sg	sg
size	vf				
type	nt				
Concretions					
abundance					
size					
type					
Cutans					
kind					
abundance					
contrast					
continuity					
Roots					
abundance	ab	ab	fw	fw	
size	f	f	f	f	
Field pH	5.5	5.5	5.5-6.0	6.0	6.0

RM3. PLATE OF SOIL PROFILE.

RT1. SOIL PROFILE DESCRIPTION.

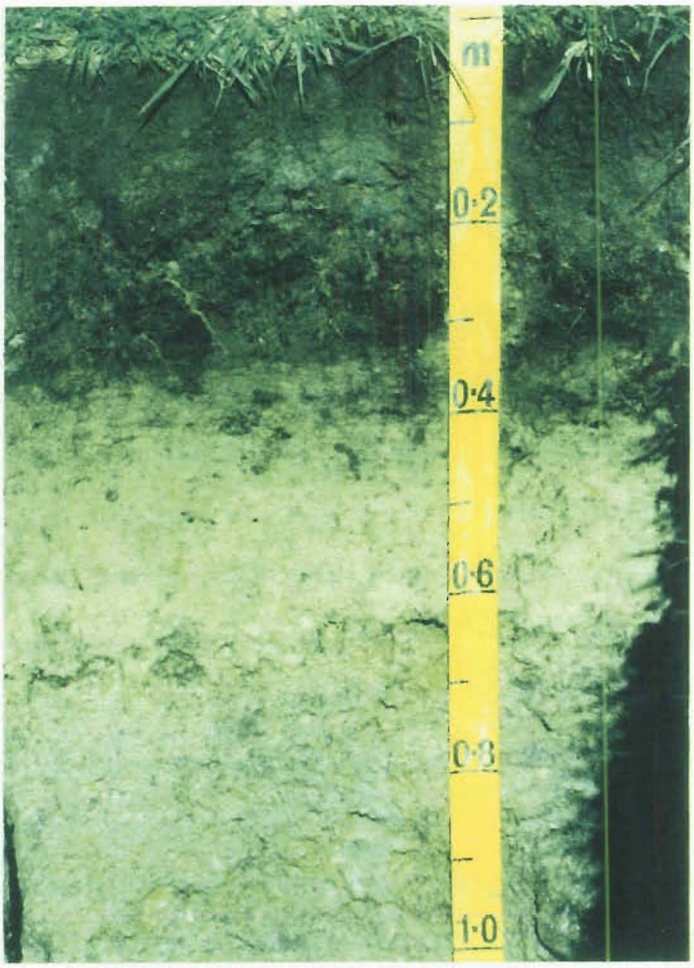
Soil Horizon	**A1**	**A2**	**2bA**	**2bBw**	**3bC**
Depth (cm)	0-10	10-38	38-50	50-85	85-130+
Boundary					
distinctness	clr	gr	gr	clr	
shape	wy	irr	irr	wy	
Moist Colour	2.5Y 3/2	2.5Y 3/2	2.5Y 4/2	2.5Y 6/4	10YR 5/8
Mottling					
abundance				fw	
size				f	
contrast				ft	
colour				7.5YR 5/6	
Texture					
Skeletal					
size and	slt.grv	slt.grv	m.grv	m.grv	m.grv
volume		slt.st	v.st	v.st	v.st
shape	sa	sa	sa	sa>sr	sa>sr
weathering	fr	fr	slt	slt	slt
Fine	zl	zl	sl	ls	s
Consistence					
Fine					
strength	w	w	w	lo	lo
failure	br	br	br		
stickiness					
plasticity					
Skeletal					
packing	P3	P3	P3	P2	P2
Structure					
grade	w	w	w	w	sg
size	vf	vf	vf	mass to vf	
type	nt	bk	nt	bk	
Concretions					
abundance					
size					
type					
Cutans					
kind					
abundance					
contrast					
continuity					
Roots					
abundance	ab	co	ma	fw	
size	f	f	f	f	
Field pH	5.0-5.5	5.0-5.5	5.5	5.5	5.5-6.0

RT1. PLATE OF SOIL PROFILE.

RT2. SOIL PROFILE DESCRIPTION.

Soil Horizon	**A**	**C**	**2bO**	**2bBr**	**3bCr**	**4bCr1**	**4bCr2**
Depth (cm)	0-10	10-25	25-32	32-45	45-62	62-80	80-110+
Boundary							
distinctness	gr	abr	abr	df	abr	clr	
shape	irr	irr	wy	irr	wy	wy	
Moist Colour	10YR 3/2	2.5Y 4/1	10YR 2/3	5YR 4/2	5YR 5/2	5R 7/1	5R 7/2
Mottling							
abundance		fw					co
size		f					f
contrast		ft					ft
colour		10YR 6/6					10YR 5/6
Texture							
Skeletal							
size and					slt.grv	v.grv	m.grv
volume						m.st	v.st
shape					sa	sa	sa
weathering					slt	slt	slt
Fine	zl	zl	peaty	sl	sl	ls	ls
Consistence							
Fine							
strength	w	fm		w	fm	lo	lo
failure	sd	sd		sd	sd		
stickiness							
plasticity							
Skeletal							
packing					P3	P3	P3
Structure							
grade	m	w		w	w	sg	sg
size	f	f		f	f		
type	nt	bk		nt	bk		
Concretions							
abundance							
size							
type							
Cutans							
kind							
abundance							
contrast							
continuity							
Roots							
abundance	co	ab	ab	c	c	f	fw
size	vf-f	vf-f	vf-f	f	f	f-md	f
Field pH	6.0	5.0	4.0	4.5	5.0	4.0	4.5

2. PLATE OF SOIL PROFILE.



RT3. SOIL PROFILE DESCRIPTION.

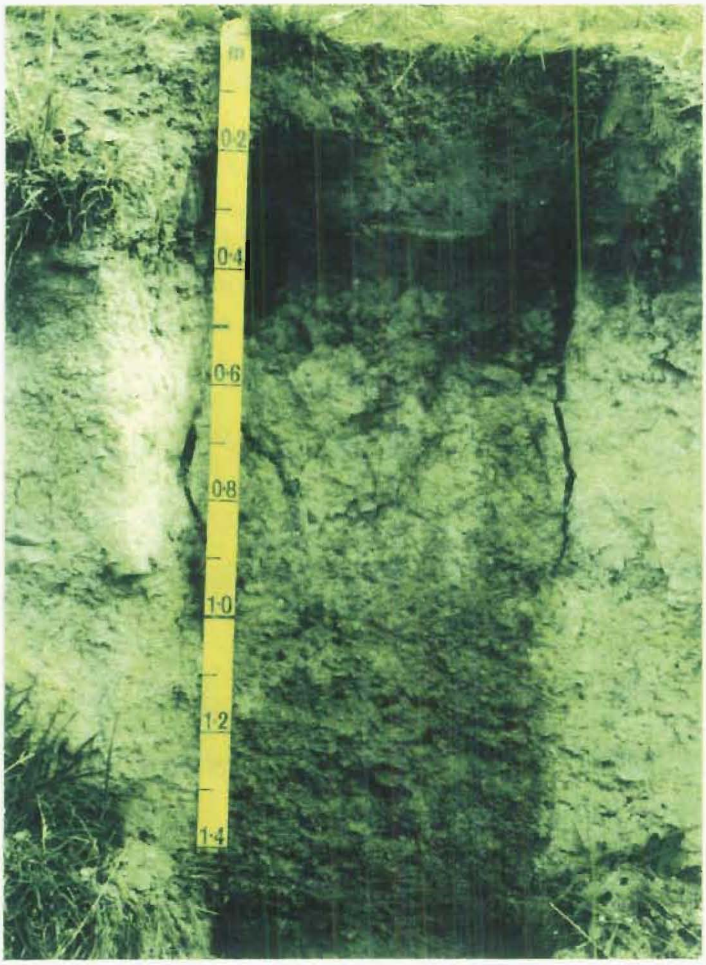
Soil Horizon	A1	Ag2	2bABg	2bBg	3bCg
Depth (cm)	0-17	17-45	45-53	53-100	100+
Boundary					
distinctness	gr	clr	gr	cl	gr
shape	irr	wy	wy	wy	
Moist Colour	2.5Y 4/1	2.5Y 4/1	2.5Y 6/2	5Y 7/3	10YR 6/4
Mottling					
abundance	fw	co	ma	ma	co
size	f	f	f	md	md
contrast	ft	ft	di	pr	di
colour	5YR 4/8	5YR 4/8	10YR 6/6	7.5YR 5/6	7.5YR 5/6
Texture					
Skeletal					
size and	slt.grv	slt.grv	slt.grv	slt.grv	v.grv
volume	slt.st	slt.st			m.st
shape	a	a	sa	a	sa
weathering	fr	fr	slt	slt	slt
Fine	zl	zl	zl	zl	sl
Consistence					
Fine					
strength	fm	fm	fm	fm	lo
failure	sd	sd	sd	sd	
stickiness					
plasticity					
Skeletal					
packing	P3	P3	P3	P3	P3
Structure					
grade	w	w	m	m	sg
size	f	f	md	md	
type	nt	nt	bk	bk	
Concretions					
abundance				co	
size				f	
type				Mn, Fe	
Cutans					
kind					
abundance					
contrast					
continuity					
Roots					
abundance	ab	ab			
size	f-md	f-md			
Field pH	6.0	6.5	6.5	6.0	6.5

RT3. PLATE OF SOIL PROFILE.

RT4. SOIL PROFILE DESCRIPTION.

Soil Horizon	**A**	**C**	**2C**	**3bAh**	**3bAB**	**3bBr**	**4bCr**	**5bCr**
Depth (cm)	0-8	8-24	24-34	34-40	40-50	50-90	90-153	153+
Boundary								
distinctness	gr	clr	clr	gr	abr	abr	abr	
shape	wy	wy	wy	irr	wy	wy	wy	
Moist Colour	10YR 3/3	2.5Y 5/2	5Y 4/1	2.5Y 4/1	2.5Y 6/1	5Y 7/2	5Y 7/2	5Y 7/3
Mottling								
abundance	fw	co	fw	fw	fw	fw	ma	ma
size	f	f	f	f	f	f	ma	c
contrast	di	di	ft	di	di	di	di	pr
colour	7.5YR 5/6	7.5YR 5/6	5YR 5/6	5YR 5/6	5YR 5/6	10YR 6/6	7.5YR 6/8	10YR 6/6
Texture								
Skeletal								
size and	slt.grv	slt.grv		slt.grv	slt.grv	m.grv	v.grv	m.grv
volume						slt.st	m.st	slt.st
shape	a	a		a	a	sa	sa	sa
weathering	fr	fr		fr	fr	slt	slt	slt
Fine	sl	sl	zl	zl	zl	sl	ls	ls
Consistence								
Fine								
strength	w	lo	w	fm	fm	fm	lo	lo
failure	sd		d	sd	sd	sd		
stickiness								
plasticity								
Skeletal								
packing	P3	P3		P3	P3	P4	P2	P2
Structure								
grade	W	mass	mass	w	w	m	sg	sg
size	f			f	f	md		
type	nt			nt	nt	nt		
Concretions								
abundance							co	co
size							f	f
type							Mn	Mn
Cutans								
kind						Fe, org		
abundance						fw		
contrast						di		
continuity						dc		
Roots								
abundance	abr	ma	co	co	fw			
size	vf	f	f	f	f			
Field pH	6.5	7.0	6.5	6.0	6.0	5.5	6.0	7.0

RT4. PLATE OF SOIL PROFILE.



SOIL CHEMICAL DATA.

Sample		(cm)	(Water)	(CaCl)	(Δ)	Carbon (%)	H_2SO_4-Soluble (me./100 g)	Oxalate %		(me./100 g)					(me./100 g)		(me./100 g)	(me./100 g)		
LM11	A	0-10	6.5	4.8	-0.7	2.8	55	0.10	0.31	3.89	0.92	0.24	0.12	0.05	0.4	0.2	5.3	5.9	5.7	91
LM12	2bAg	10-20	5.6	4.8	-0.8	1.7	65	0.09	0.31	3.05	0.77	0.17	0.09	0.04	0.3	0.1	4.1	4.6	4.4	90
LM13	2bAg	20-30	5.6	4.8	-1.0	1.6	37	0.10	0.45	2.92	0.85	0.12	0.10	0.03	0.6	0.2	4.0	4.8	4.6	84
LM14	2bABg	30-50	5.6	4.4	-1.2	1.3	12	0.13	0.35	1.95	0.85	0.05	0.13	0.01	1.2	0.4	2.8	4.4	4.0	64
LM15	2bBr	50-65	5.7	4.5	-1.2	0.43	4	0.10	0.22	1.59	0.70	0.05	0.12	0.01	1.8	0.4	2.5	4.7	4.3	53
LM16	2bBxg	65-80	5.5	4.5	-1.0	0.12	9	0.13	0.26	2.37	1.40	0.08	0.16	0.04	2.8	0.4	4.1	7.3	6.9	56
LM17	2bBx	80-100	5.6	4.2	-1.4	0.00	42	0.13	0.43	2.15	1.62	0.11	0.12	0.01	1.7	0.6	4.0	6.4	5.8	63
LM18	2bBx	100-120	5.5	4.4	-1.1	0.00	45	0.12	0.31	2.49	1.75	0.11	0.12	0.02	0.1	0.1	4.5	4.8	4.6	94
LM19	2bBx	120-140	5.8	3.9	-1.9	0.00	52	0.11	0.46	3.51	1.64	0.14	0.17	0.02	0.6	0.1	5.5	6.2	6.1	88
LM110	2bBx	140-160	5.8	4.8	-1.0	0.00	50	0.07	0.26	3.56	1.80	0.16	0.19	0.01	0.4	0.1	5.7	6.2	6.1	92
LM111	2bBx	160-180	5.8	4.8	-1.0	0.00	44	0.07	0.27	3.75	1.86	0.19	0.17	0.01	0.2	0.2	6.0	6.3	6.2	94
LM112	2bBx	180-200	6.8	5.1	-0.7	0.00	49	0.07	0.35	3.75	1.77	0.18	0.19	0.02	0.2	0.2	5.9	6.2	6.1	95
LT11	A	0-10	5.9	5.3	-0.6	3.5	37	0.14	0.86	8.67	1.24	1.07	0.10	0.04	0.0	0.2	11.1	11.3	11.1	99
LT12	A	10-20	5.5	5.0	-0.5	2.5	32	0.13	0.90	9.42	1.30	1.28	0.12	0.05	0.0	0.2	12.2	12.3	12.2	99
LT13	AB	20-30	5.3	4.7	-0.6	1.9	26	0.14	0.79	6.14	0.99	0.58	0.10	0.02	0.1	0.2	7.8	8.2	8.0	96
LT14	AB	30-40	5.0	4.3	-0.7	1.4	19	0.13	0.66	3.52	0.83	0.36	0.10	0.02	1.1	0.4	4.8	6.3	5.9	77
LT15	Bg	40-55	5.1	4.2	-0.9	1.0	6	0.11	0.36	2.02	0.88	0.21	0.06	0.01	1.5	0.8	3.2	5.3	4.7	60
LT16	Bg	55-70	5.3	4.2	-1.1	0.61	7	0.10	0.19	1.69	0.95	0.11	0.06	0.01	1.6	0.4	2.8	4.9	4.5	58
LT17	Cr	70-90	5.6	4.3	-1.3	0.37	9	0.09	0.25	1.65	0.75	0.10	0.12	0.01	1.3	0.3	2.6	4.2	3.9	62
LT18	2Cr	90-100	5.4	4.1	-1.3	0.18	12	0.10	0.28	2.50	1.07	0.10	0.10	0.02	1.3	1.4	3.6	6.5	5.1	59
RT21	A	0-10	6.3	6.0	-0.3	7.7	62	0.11	0.33	16.33	1.29	0.91	0.06	0.01	0.0	0.1	16.6	16.7	16.6	99
RT22	C	10-20	5.0	3.9	-1.1	5.1	49	0.15	0.32	2.93	0.37	0.44	0.03	0.00	3.1	0.4	3.8	7.2	6.9	52
RT23	2bO	20-30	4.5	3.3	-1.2	16.5	20	0.25	1.1	6.22	0.53	0.33	0.08	0.00	5.8	3.4	7.2	16.3	13.0	44
RT24	2bBr	30-45	4.0	3.2	-0.8	2.4	2	0.08	0.16	0.84	0.10	0.11	0.10	0.00	4.0	2.7	1.2	7.8	5.1	15
RT25	3bCr	45-60	4.1	3.5	-0.6	1.3	1	0.08	0.04	0.66	0.10	0.09	0.02	0.00	4.2	1.1	0.9	6.2	5.0	14
RT26	4bCr1	60-80	4.2	3.6	-0.6	0.34	9	0.06	0.06	0.70	0.12	0.09	0.03	0.00	2.7	1.1	0.9	4.6	3.6	20
RT27	4bCr2	80-100	4.1	3.4	-0.7	0.18	26	0.07	0.21	0.85	0.15	0.11	0.03	0.00	2.2	0.4	1.1	3.7	3.3	31
RT11	A1	0-15	5.2	4.7	-0.5	3.0	52	0.10	0.37	4.93	0.65	0.29	0.14	0.03	0.2	0.1	6.0	6.3	6.2	96
RT12	A2	15-30	5.2	4.1	-1.1	1.6	41	0.12	0.41	2.47	0.26	0.11	0.07	0.02	1.7	0.3	2.9	4.6	4.6	81
RT13	2bA	30-45	5.1	3.8	-1.3	1.4	30	0.15	0.42	2.08	0.24	0.11	0.09	0.01	2.2	0.3	2.5	5.1	4.8	50
RT14	2bBw	45-60	5.6	4.0	-1.6	0.43	15	0.13	0.35	1.69	0.20	0.06	0.05	0.01	2.9	0.2	2.0	5.1	4.9	40
RT15	2bBw	60-80	5.6	4.3	-1.3	0.05	16	0.12	0.31	1.55	0.26	0.06	0.06	0.00	2.7	0.7	1.9	5.3	4.6	36
RT16	3bC	80-100	5.5	4.1	-1.4	0.05	31	0.15	0.31	1.34	0.29	0.06	0.07	0.00	1.9	0.3	1.8	3.9	3.7	45
RT17	3bC	100-120	5.4	4.1	-1.3	0.02	42	0.11	0.28	1.39	0.39	0.10	0.06	0.00	1.4	0.1	1.9	3.5	3.3	56
CM31	A	0-10	5.9	4.3	-1.6	2.9	39	0.10	0.31	3.57	1.06	0.32	0.04	0.03	0.1	0.2	5.0	5.4	5.2	93
CM32	A	10-20	5.7	4.6	-1.1	2.0	28	0.10	0.30	2.74	0.81	0.22	0.04	0.02	0.2	0.2	3.6	4.2	4.1	91
CM33	2bA	20-30	5.3	4.0	-1.3	1.8	34	0.13	0.39	2.37	0.66	0.28	0.04	0.02	0.5	0.2	3.4	4.1	3.9	83
CM34	2bA	30-40	5.2	3.8	-1.4	1.8	38	0.14	0.40	3.07	0.65	0.50	0.06	0.02	0.6	0.2	4.3	5.1	4.9	85
CM35	2bAB	40-50	5.4	4.2	-1.2	0.92	31	0.14	0.40	2.49	0.50	0.49	0.05	0.01	0.6	0.2	3.5	4.3	4.2	82
CM36	2bBC	50-65	5.7	4.5	-1.2	0.53	24	0.09	0.28	2.05	0.39	0.40	0.04	0.01	0.6	0.1	2.9	3.6	3.5	79
CM37	2bBC	65-80	5.6	4.6	-1.0	0.31	19	0.08	0.25	2.50	0.38	0.36	0.46	0.00	0.3	0.1	3.7	4.1	4.0	90
CM38	3bC	80-100	6.0	5.3	-0.7	0.15	32	0.07	0.22	3.13	0.27	0.15	0.08	0.00	0.1	0.0	3.6	3.7	3.7	98
CM39	3bC	100-120	6.1	5.7	-0.4	0.11	48	0.07	0.20	2.74	0.24	0.10	0.02	0.00	0.0	0.0	3.1	3.1	3.1	100
CM41	A	0-10	5.5	4.8	-0.7	2.8	59	0.09	0.30	3.58	0.64	0.76	0.08	0.03	0.2	0.1	5.1	5.3	5.2	95
CM42	A	10-20	5.2	4.3	-0.9	0.30	59	0.07	0.27	2.07	0.42	0.33	0.14	0.02	0.6	0.3	3.0	3.9	3.5	77
CM43	C	20-40	5.4	4.3	-1.1	0.38	19	0.04	0.09	1.80	0.28	0.21	0.01	0.01	0.1	0.4	2.3	2.6	2.4	83
CM44	C	40-60	5.9	5.2	-0.7	0.06	48	0.03	0.06	1.91	0.23	0.13	0.01	0.01	0.0	0.2	2.3	2.5	2.3	93
CM45	2bAg	60-80	5.7	5.5	-0.2	0.03	52	0.03	0.18	2.55	0.29	0.14	0.02	0.01	0.0	0.1	3.0	3.1	3.0	98
CM46	3Cc	80-95	6.1	5.7	-0.4	0.15	61	0.04	0.43	3.08	0.33	0.15	0.02	0.00	0.0	0.0	3.6	3.8	3.8	99
CM47	4C	95-110	6.1	5.7	-0.4	0.31	52	0.03	0.35	2.45	0.28	0.11	0.02	0.00	0.0	0.1	2.9	2.9	2.9	96
CM48	5C	110-130	6.4	5.8	-0.6	0.17	52	0.03	0.04	2.13	0.25	0.11	0.02	0.00	0.0	0.0	2.5	2.5	2.5	99

APPENDIX C

CARBON DATE ANALYSIS.

UNIVERSITY OF WAIKATO
RADIOCARBON DATING LABORATORY

AGE REPORT

Your samples have had their radiocarbon ages determined. Please ammend the significance details, and return a copy of the ammendments to the laboratory to upgrade our files.

The results are laid out in the style utilised by the journal *Radiocarbon.* The parameters are as follows:

			Conventional age ± error
Wk number	User number	$D^{14}C$ (‰)	$\delta^{13}C$(‰)

Please note the following :

1. **The conventional age** (or Libby age) is calculated using : the Libby half-life of 5568 years, isotopic fractionation correction; NBS oxalic acid (* 0.95) as "modern" with AD 1950 as reference year; and assumption of constancy in atmospheric radiocarbon levels. This radiocarbon age is normally selected for publication, and is always accompanied by the appropriate error term and Wk number.

2. Quoted errors are based upon counting statistics alone and are based upon ±1 standard deviation.

3. The **new age** is calculated from the new half life of 5730 years.

4. The ^{14}C depletion ($D^{14}C$), is expressed in ‰ wrt 95% NBS oxalic acid.

5. The isotopic fractionation correction ($\delta^{13}C$) is expressed in ‰ wrt PDB.

6. The marine correction (reservoir effect) can be applied to intertidal carbonates as follows : NZ intertidal species - subtract 336 years; Australian intertidal species - subtract 450 years.

7. Sample ages are reported as MODERN when the reservoir-corrected conventional age is less than 200 years. They are reported as >MODERN with ages younger than 1950.

3680 ± 60

Wk - 2347 Bullock Ck -367.4 ± 4.1 ‰ $\delta^{13}C$ = -27.8 ‰

Other parameters :

Dilution	=	93.8% sample
New age	=	3790 ± 60
% Modern	=	63.3 ± 0.4
Count time	=	1973 mins.

Significance - (RH): estimates age of loess surface, giving an absolute date of the oldest veneered fan surface.